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APPLICATION OF CONCURRENT ENGINEERING METHODS TO THE DESIGN OF AN AUTONOMOUS AERIAL ROBOT

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A THESIS
Presented to
The Academic Faculty

by

Captain Stephen A. Ingalls

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In Partial Fulfillment
of the Requirements for the Degree
Master of Science

Georgia Institute of Technology
December 1991

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Statement A per telecon Capt Jim Creighton
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DEDICATION

To Cara, Zachary, and Andrew, whose patience I've succeeded in testing once again...

...and to the 1991 National League Champion Atlanta Braves, whose miraculous season, stretching all the way to the 'October Classic', resulted in this document's completion being delayed much too long...

...resulting in my having to test Cara's, Zachary's, Andrew's, and my advisory committee's patience far beyond what would normally be considered reasonable.

ACKNOWLEDGEMENTS

It is difficult to fathom the amount of energy which was expended in this effort. The many hours given voluntarily by students, faculty, and staff at the Georgia Institute of Technology have gone, for the most part, unnoticed.

Our industrial partners: Pacific RPV, Incorporated, Guided Systems Technologies, the United States Army Aerostructures Directorate, and the Mitre Corporation provided an immense amount of technical support and sound advice.

Were it not for the support of Richard Daniel, Joe Hulsey, Ken Mauragas, Howard Cooley, and Bob Gryder, the aircraft would certainly have had even a more significant impact on the team's performance than it eventually had. Their patience and unselfishness represented a huge knowledge resource the team could never hope *to gain on its own.*

The Schools of Aerospace Engineering, Civil Engineering, Mechanical Engineering, Electrical Engineering, and the College of Computing provided significant contributions to the most worthwhile effort I've been involved in while at Georgia Tech. In particular, the team owes a great deal of thanks to the Aerospace Engineering shop for their words of advice when a 'get lost' was probably more appropriate.

Dr. Daniel P. Schrage, Dr. J.V.R. Prasad, Dr. Ron Arkin, Dr. George Vachtsevanos, Dr. Bonnie Heck, Dr. Steve Dickerson, and Dr. Nelson Baker allowed the student contingent to truly control the effort and kept the team's leaders on path when so many things seemed to be 'up in the air'.

Finally, for getting us into rooms, letting us have access to his VCR, showing us how to set up the Georgia Tech convention backdrop, and letting me use his computer to type this document, Cliff McKeithan always seemed to facilitate whatever the team needed behind the scenes. We noticed.

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SUMMARY

This paper documents the year-long efforts of a multidisciplinary design team to design, build, and support an autonomous aerial robotics system. The system was developed to participate in the Assocation for Unmanned Vehicle System's (AUVS) First International Aerial Robotics Competition which was held in Atlanta, Georgia on the Georgia Tech campus on July 29th, 1991.

As development time and budget were extremely limited, the team elected to attempt the design using concurrent engineering design methods. These methods were validated in an IDA study by Winner [1] in the late-1980s to be particularly adept at handling the difficulties to design presented by these limitations.

A significant portion of the team's early efforts were aimed at establishing an appropriate design environment: understanding the problem and soliciting necessary resources. Market evaluations of candidate hardware components occupied the team for most of the initial design cycle, with selection c^{f} an aerial vehicle, the Pacific RPV 'Bruiser', accomplished in late-November 1990.

With receipt and evaluation of the system's base, the aerial vehicle, preliminary design of a variety of payload components was initiated in January 1991. Many of these subsystems were designed from the 'ground up', while some components were loaned to the team and modified for the competition's specific requirements. Flight testing with the aerial vehicle revealed a number of mechanical problems with the aircraft's design and manufacture. These difficulties eventually trickled into test schedules and system-level

planning documents, making any long-term component testing, validation, and integration impossible.

Even with the Bruiser's difficulties, significant work on all major subsystems was accomplished, although integration of these components into a working system was still in its infancy on competition day. Further mechanical malfunctions of the aircraft, difficulties with communications nodes, and immaturity of other components forced the team's withdrawal from the event, but not before an all out effort was made up until called for their heat on competition day.

The team, while accomplishing a large portion of the design task, was less than successful in implementing all facets of concurrent engineering. While under budget, the system's quality, as judged by the AUVS on Quality Function Deployment documents, was lower than other competing systems in six of seven listed customer categories. Lastly, although the competition-prescribed design cycle deadlines were not met, none of the five competing team's produced a system capable of completing any significant portion of the mission, possibly indicating an unrealistic product development cycle from the beginning.

Regardless, application of several different quality engineering tools was accomplished, although without significant thought as to their timing in the development cycles and the results intended from the use of each tool. The team worked from beginning to near project completion in a 'design deficit', having fewer resources than required to accomplish the remaining portions of the system's design.

All in all, the hand-on experience and interface with a variety of technical specialties represented on the design team resulted in a positive experience. Lessons learned, one of the ten tenets of successful concurrent engineering implementation, have been focused on in order to provide impetus to next year's design team.

INTRODUCTION

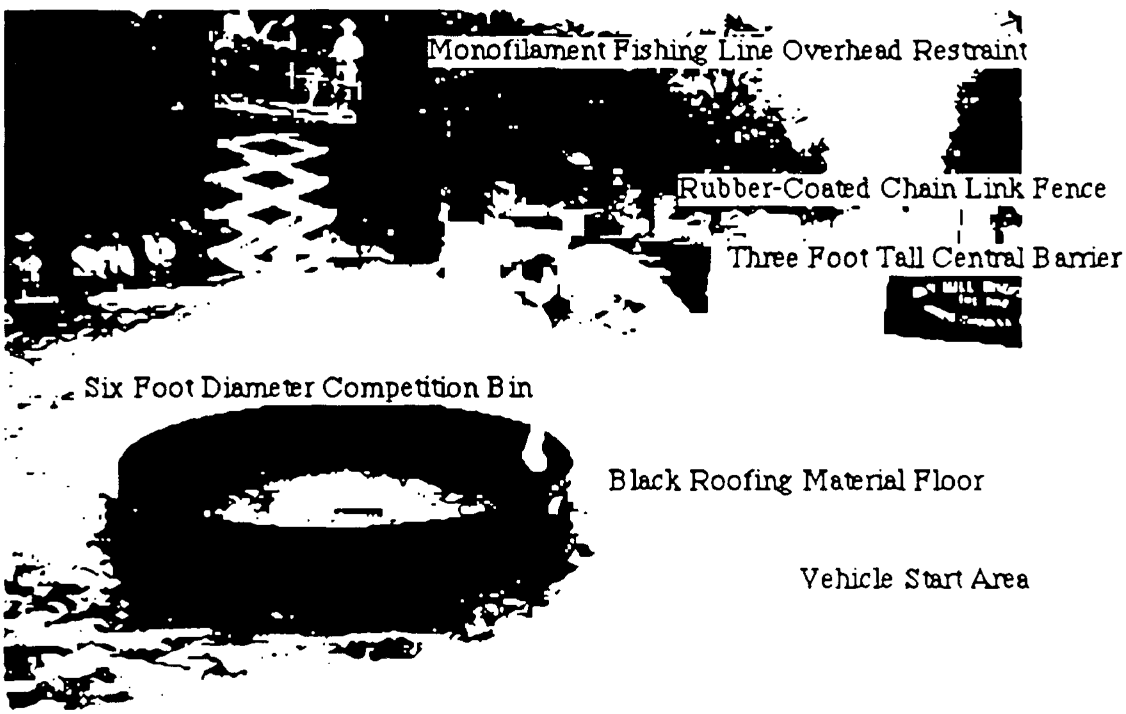
Why Undertake Development of an Aerial Robot?

In late-July 1990, the Association for Unmanned Vehicle Systems (AUVS) announced the First International Aerial Robotics Competition. This competition took place on the Georgia Tech campus on July 29th, 1991 and exhibited talents of five student design teams from major engineering universities around the United States.

This competition required development of an unmanned and autonomous aerial robot system. The system could be preprogrammed or intelligent, but was not to be flown by a student operator. Distribution of computational power within the system, either airborne or at a ground station, was left to the team's discretion. Data link from the aerial vehicle to the ground could be accomplished using a variety of means, however, no physical tethers or other 'entangling encumbrances'[1] were allowed. The competition-specified mission was accomplished completely inside a volleyball court bordered by a black polystyrene plastic-covered sand floor, rubber-coated chain link fence along all four sides, and monofilament fishing line periodically stretched both longitudinally and laterally across the top of the court (approximately 9.75 feet above the arena surface) [Figure 1]. The aerial vehicle was

1. Association for Unmanned Vehicle Systems, "Official Rules", Association for Unmanned Vehicle Systems First International Aerial Robotics Competition, January 1991, p. 1.

Figure 1 - First International Aerial Robotics Competition Arena



required to start in a specified area adjacent to a corner of the court, take off, and transport as many metallic target disks as possible from one six foot diameter ring to another within three minutes. A wooden barrier, three feet in height, was erected across the center of the court, and existing metal poles, used normally to mount a volleyball net, were left as obstacles to movement [Figures 2-4]. In addition to the three minute limitation for executing the prescribed mission, an additional three minutes was allotted each team to start their aircraft, and a final three minute segment allowed to set up external navigation cues or control stations, as required by the various systems.

Disks were designed so that a variety of means could be utilized for retrieval: tactile, suction, or magnetic. Two circular steel plates, three inches in diameter, were attached to the top and bottom of a 3/8" tall aluminum tube. The cavity inside the tube was filled with lead shot to increase each disk's weight to four ounces. Six of these Day-Glo orange-colored disks [Figure 5] were randomly distributed within the 'source' bin.

Vehicles could be no larger than six feet in any dimension, although telescoping arms, appendages, and wings could be deployed once airborne and not violate this restriction[2]. A safety mechanism was also required which could terminate system operation should the aircraft become unstable or begin substantial uncommanded deviation from the desired flight trajectory.

The unique challenges presented by this competition required collaboration of several technical disciplines and allowed student engineers to advance designs beyond the

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2. Association for Unmanned Vehicle Systems, "Questions and Answers Concerning the First International Aerial Robotics Competition", Association for Unmanned Vehicle Systems First International Aerial Robotics Competition, January 1991, p. 1.

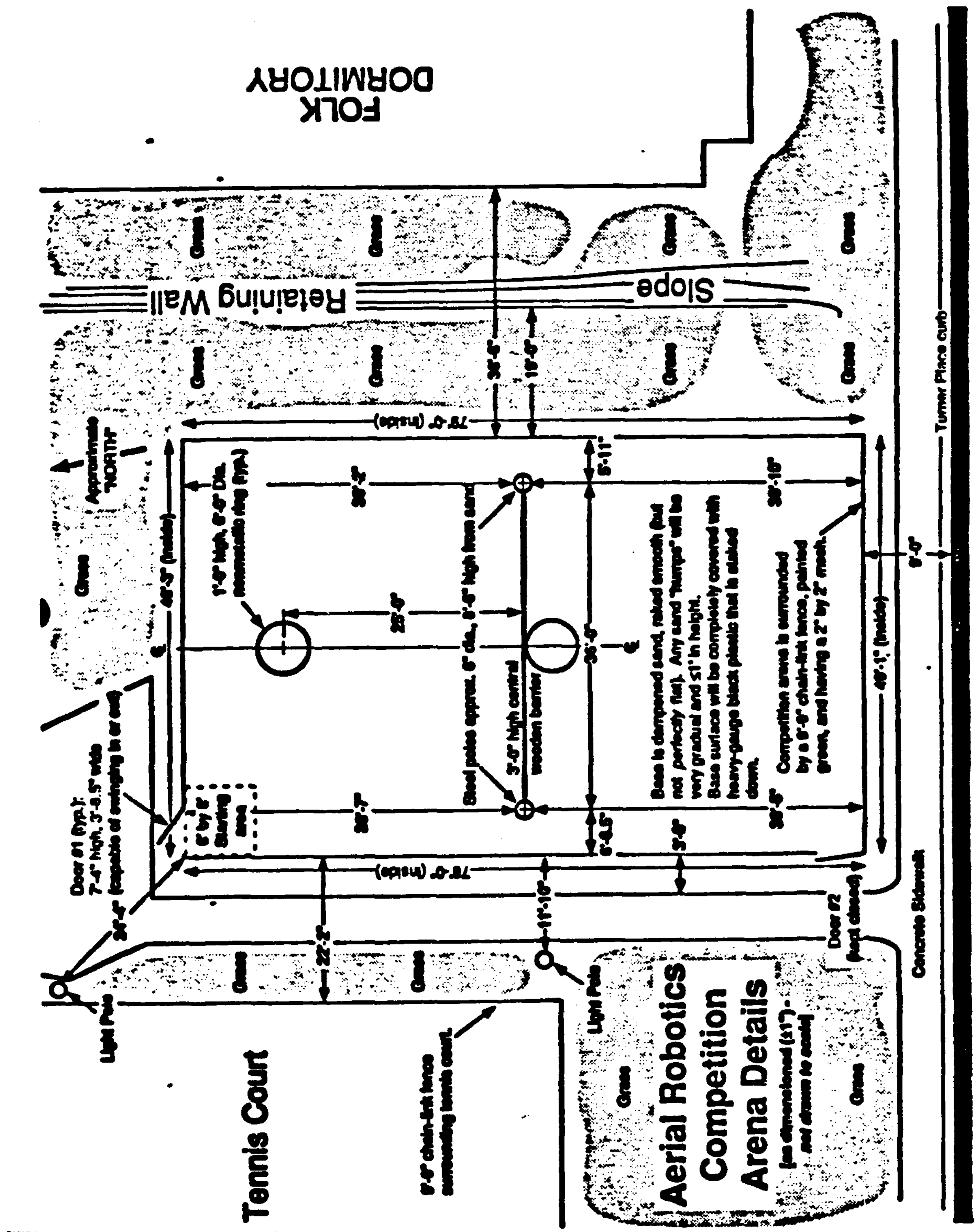

Figure 2 - Aerial Robotics Competition Arena Details

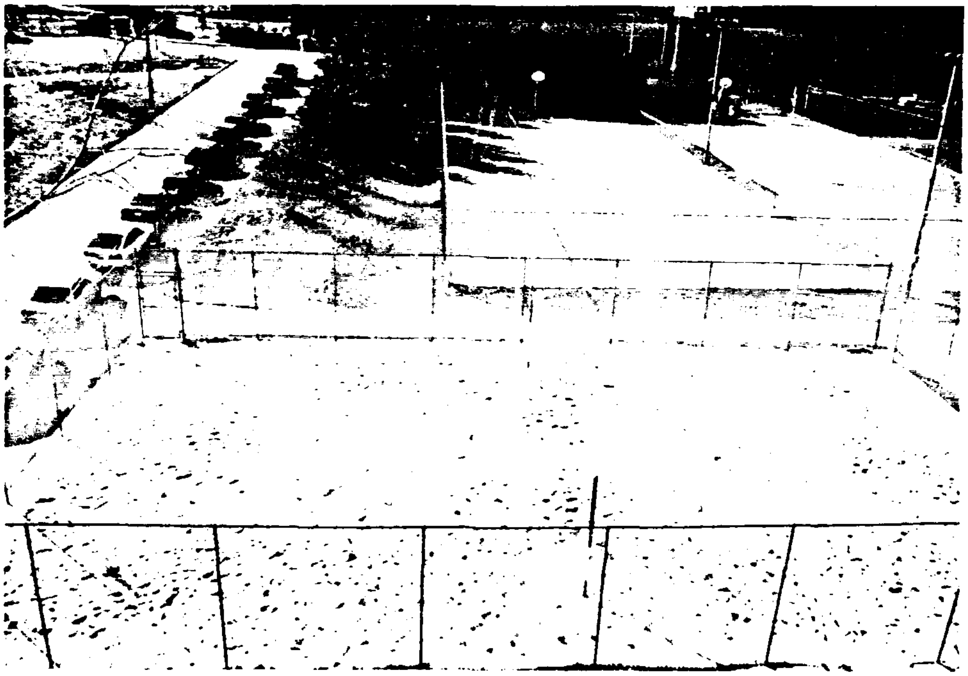

Figure 3 - Aerial View of the Arena from East looking West

Figure 4 - Ground View of Arena from the South looking North

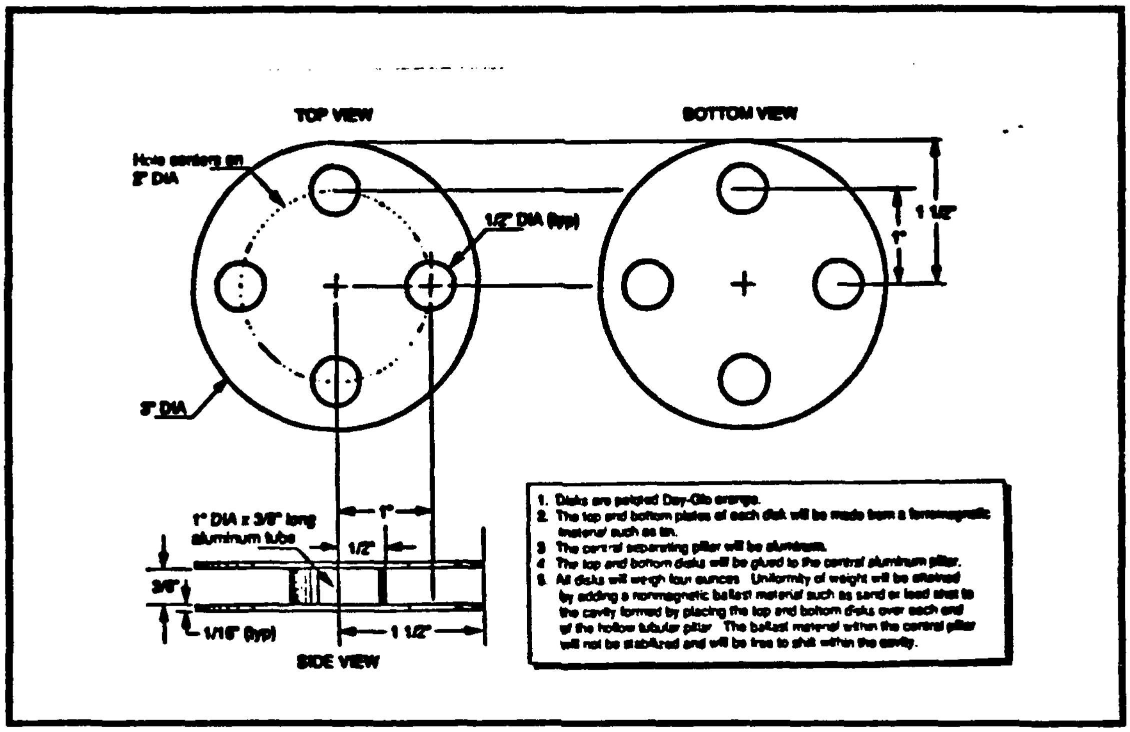

Figure 5 - Target Disk Geometry and Technical Data

preliminary (primarily paper) stage. Additionally, multidisciplinary requirements of the AUVS' competition, coupled with a restrictive one-year design cycle, created the perfect 'laboratory' environment for application of concurrent engineering principles.

Various management and engineering design courses throughout the Georgia Tech curriculum individually focus on the study and application of these techniques. Few examples were, however, available which showed the result of applying concurrent engineering tenets at the conceptual design point and highlighted their ultimate impact on manufacturing, operation, and support of a hardware component or system downstream in the design cycle.

It was with this competition and the opportunities it offered as a backdrop, that a multi-year, multi-phase concurrent engineering pilot project was initiated. Phase I objectives were to develop the proposed aerial robot system toward application in the AUVS competition environment. Follow-on phases were envisioned to use this baseline system as a test bed for applicable emerging technologies. The remainder of this paper seeks to further define the design environment and chronicle the design team's phase I efforts.

CHAPTER I

WHAT IS CONCURRENT ENGINEERING AND WHY WAS IT SO IMPORTANT TO THIS PROJECT?

Concurrent Engineering

Winner [1] defines concurrent engineering as a "systematic approach to the integrated, concurrent design of products and related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements."[3] More recently, Clausing [2] introduced the concept of "world-class concurrent engineering", which he described as a combination of "three major elements: (1) Management (process, organization, and people styles); (2) Enhanced Quality Function Deployment (EQFD); and (3) Quality Engineering for Robust Design."[4]

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3. Robert I. Winner et al., "The Role of Concurrent Engineering in Weapons System Acquisition", Institute for Defense Analyses Report R-338, December 1988, p. 2.

Concurrent engineering, in order to be successful, requires that consideration of processes traditionally ignored until later in the product development cycle are included as facts bearing on the problem during formulation and selection of design options. This necessarily requires communication between engineers normally isolated within their 'time segment' of the design process, and who typically speak in technical languages unfamiliar to other design engineers. Therefore, management capable of interpreting input from participants in product design and manufacture, and managing this 'deluge' of information toward a common design goal, is imperative.

Apparent in the definitions above are tenets of the probably more recognizable systems and quality engineering disciplines.

Systems Engineering.

Systems engineering evolved out of the need to manage large, very complex, highly technical projects conducted over severely constrained development times. Concurrently, the emergence of technical specialization throughout the 1950s and 1960s resulted in over 250 recognized specialties, all of which required information from, and provided data to, the development process. Coordinating this exchange required significant effort by the systems engineering and technical direction coordinator, and resulted in the need for a combined technique to address both management and technical processes as applied to design[5].

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4. Don Clausing, "Concurrent Engineering", Design and Productivity International Conference, Honolulu, Hawaii, February 1991, p. 1.

5. Defense Systems Management College, Systems Engineering Management Guide, 2nd Edition, December 1986, p. 1.2.

Quality Engineering.

While formal systems engineering techniques have been around only since the 1950s, quality engineering methods find their origins in the early 1900s with the industrial revolution[6]. Engineering drawings and informal inspection procedures along the manufacturing line gradually yielded to the more formal statistical process control (SPC) techniques initiated during the 1930s[7]. While traditionally considered applicable only during the manufacturing stage of a product's life cycle, studies indicate utility from their application during the design phase, as well as their application's impact on design in an iterative environment[8]. These methods involve data collection and evaluation of processes and product characteristics along the production line.

More recent are the Japanese initiatives in quality engineering. Having evolved over the last thirty to forty years, these techniques are less tools, and more underlying theme, in product design and manufacture. Total Quality Control (TQC) is implemented in every department, by every employee, and involves improvement of everything the company attempts to do[9].

Some quality techniques, while applicable during the manufacturing stage, are equally useful during conceptual design. Taguchi parameter design optimization methods (PDOM) attempt to identify which engineering parameters are easiest and most cost-

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6. Winner et al., pp. 14-15.

7. Ibid., pp. 14-15.

8. Ibid., p. 14.

9. Yoshinori Iizuka, "The Japanese Way of TQC", The University of Tokyo, Presentation Charts· ITT Japan Study Mission Report, 1989, p. 1.

effective to control while maintaining a requisite product quality [2]. Quality Function Deployment (QFD), a graphical mapping technique first implemented in 1972 at Mitsubishi's Kobe shipyard[10], aids in translating customer requirements into product and process characteristics [3,4].

Putting it All Together.

A useful analogy in understanding how concurrent engineering incorporates the best of systems and quality engineering is a road network. Concentrating on the product design, the design cycle can be compared to the route which must be negotiated and the engineering techniques to the road system over which various design and manufacturing engineers must travel.

Statistical process control techniques allow the manufacturing engineer to 'drive' from downstream in the design only as far as the beginning of the production cycle before reaching a 'dead end'. This technique is primarily a management action and not one in which the line worker will likely become involved. The Japanese, on the other hand, through implementation of methods like Taguchi PDOM and QFD, can 'drive' along the design cycle from conceptual design through product manufacture and support [Figure 6]. Because quality permeates Japanese organization structure, both management and labor are equally affected, represented by the multi-tiered highway.

Systems engineering techniques are primarily management and technologies processes applied early in the design and applicable through the product's complete life cycle[11] [Figure 7].

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10. John R. Hauser and Don Clausing, "The House of Quality", Harvard Business Review, May-June 1988, p. 63.

11. Defense Systems Management College, p. 1.2.

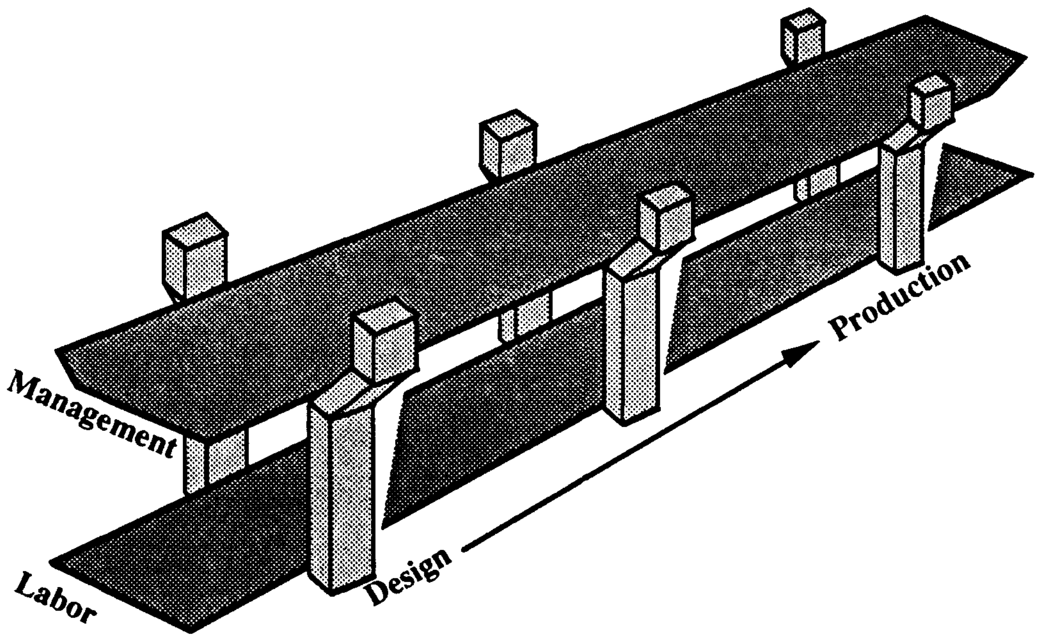


Figure 6 - Analogy of Quality Engineering to a Highway Structure

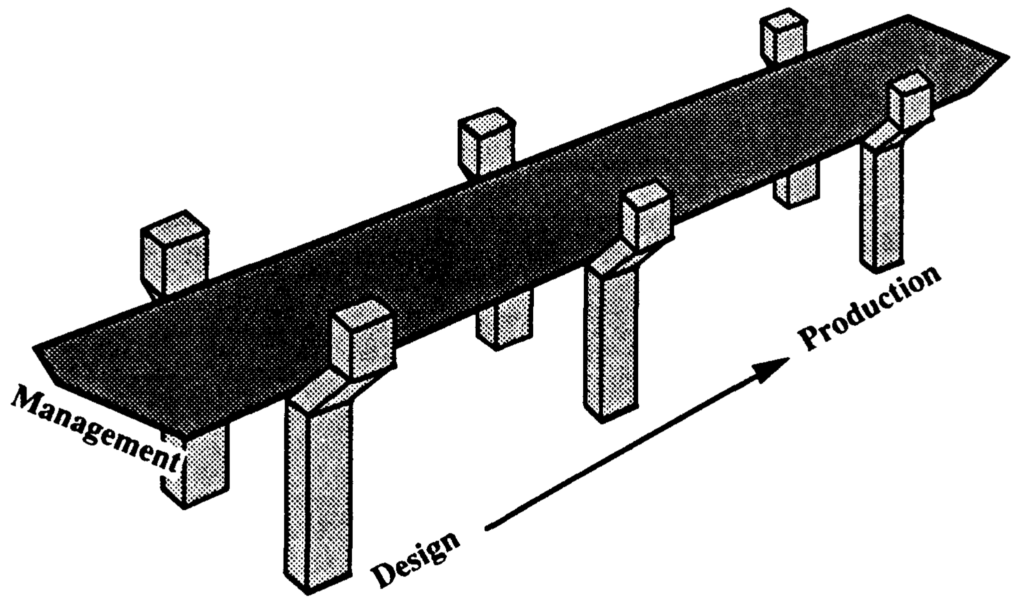


Figure 7 - Analogy of Systems Engineering to a Highway Structure

Concurrent engineering may be viewed as the 'junction' of these techniques within some methodology [Figure 8]. One can envision the clover-leaf exchange which allows engineers from anywhere in the design or manufacturing process access to any other point in the product's development cycle.

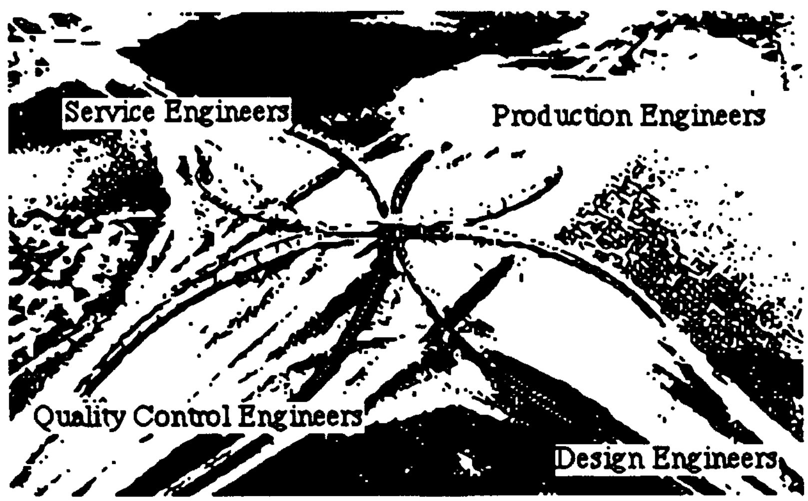


Figure 8 - 'The Concurrent Engineering Exchange'

Key to successful long-term application of concurrent engineering is a fully-integrated computer-aided design and manufacturing environment [5]. An automated design environment may eventually allow engineers the ability to avoid 'building the road', but instead, the requirement only to 'model the road' while accomplishing the same design goals.

The Aerial Robot's Design Environment

A design environment may best be described as the motivation for, and resources available to, accomplish a given design. Having already discussed the AUVS-sponsored competition, a brief overview of time, manpower, budget, facilities, and team experience follows.

Time.

Three-hundred forty-three (343) design days were available from the team's first organization meeting on August 20th, 1990 to competition day on July 29th, 1991. After subtracting time for quarterly class breaks and holidays, the team was left with less than forty-three (43) weeks in which to develop the system. This represents a best-case design cycle as time away from the aerial robotics effort to pursue other academic requirements (mid-term and final examinations, course projects, etc.) are not included.

Manpower.

A time-history of team participation is graphed in Figure 9. Multidisciplinary interaction required by the design is reflected in a similar graph of participation by technical discipline in Figure 10.

Budget.

Just over $18,000 was eventually gathered from various university and industrial sources. An additional $13.3K in donated and loaned equipment was provided the design team for application throughout the system [Figure 11]. Equipment loans included items both intended for use in the ultimately fielded system and for testing/validation. Only those loaned hardware components utilized on the final system are included in the figure.

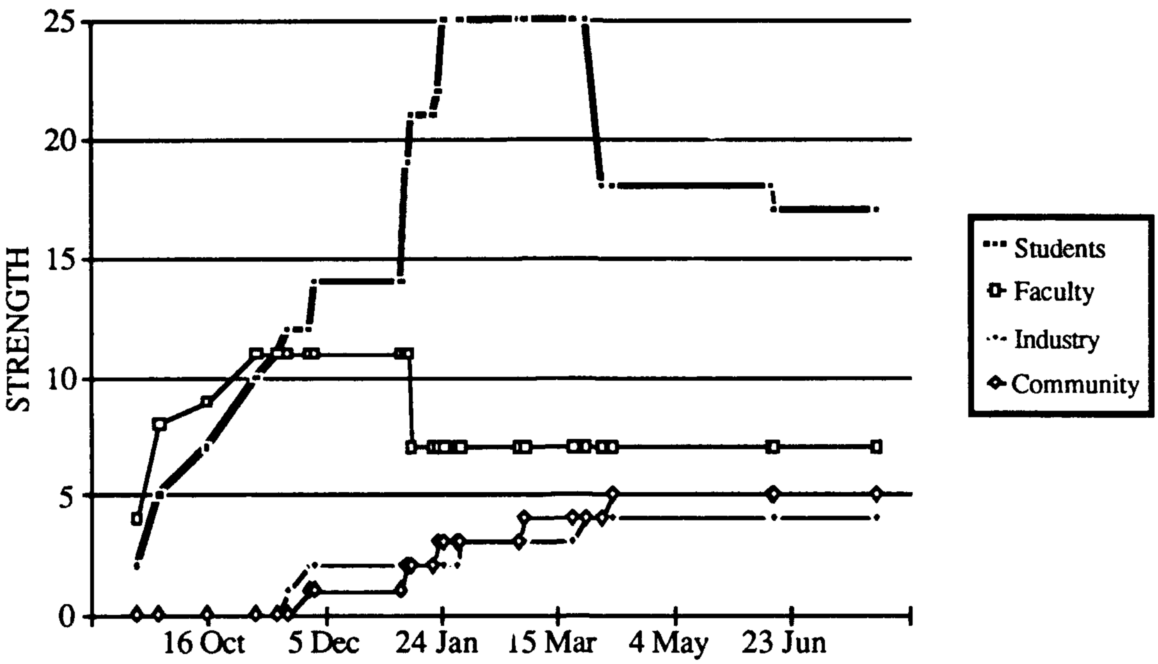


Figure 9 - Team Strength vs. Time

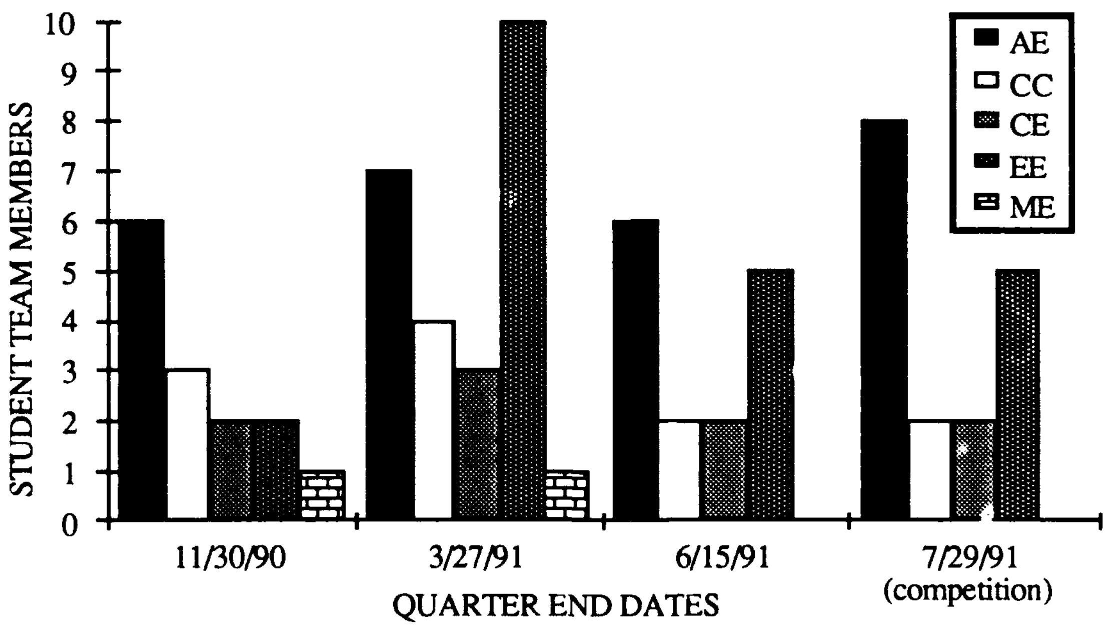


Figure 10 - Student Technical Discipline vs. Time

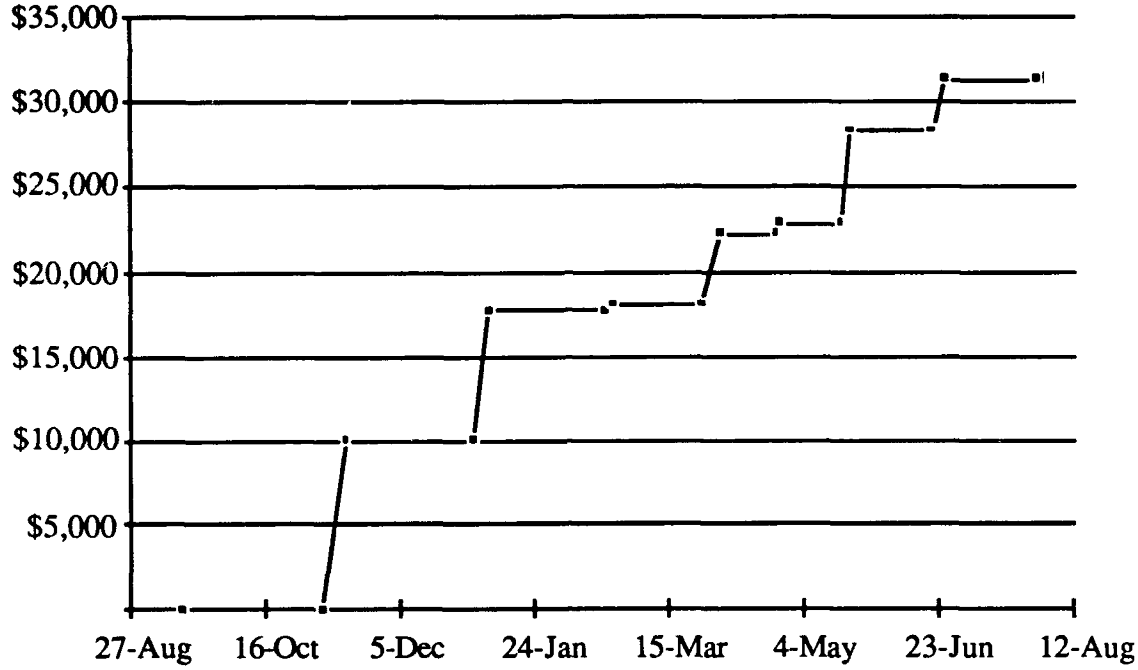


Figure 11 - Capital and Equipment Resources vs. Time

Not adequately recorded was the contribution by various electronics companies, in particular, who provided component samples for use in various circuits embedded in key components throughout the system.

Facilities.

No dedicated facilities were made available until December 1990, when office space was allocated to the team. In January 1991, mechanical malfunction allowed the group access to an adjacent bay of a hover test facility. This area served as the team's ultimate focal point for the remainder of the design cycle.

Electrical engineering students working on other research were able to use lab space allocated them to work on the aerial robotics design effort.

A final area was provided to lay out a scale competition arena for use in testing/validating the proposed vision system in its navigation application.

Test flights, for the most part, were conducted on the roof of Georgia Tech's student parking garage.

It should be noted that integration efforts were not well served by the "patchwork" nature of available facilities [Figure 13].

Experience.

None of the team's student or faculty members had radio-control (R/C) helicopter experience. Fortunately, volunteer participation by members from two local R/C clubs overcame this difficulty.

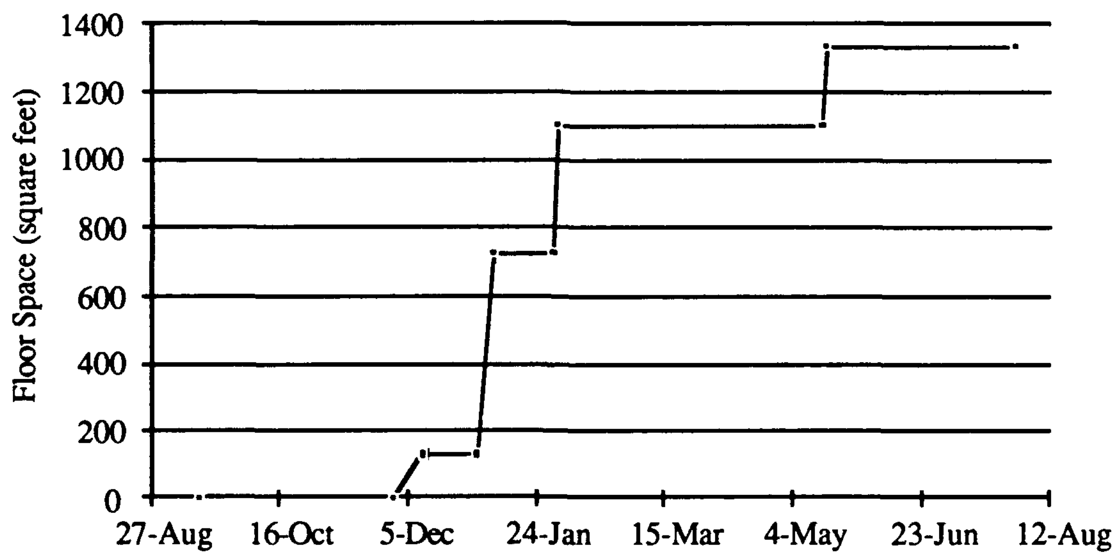
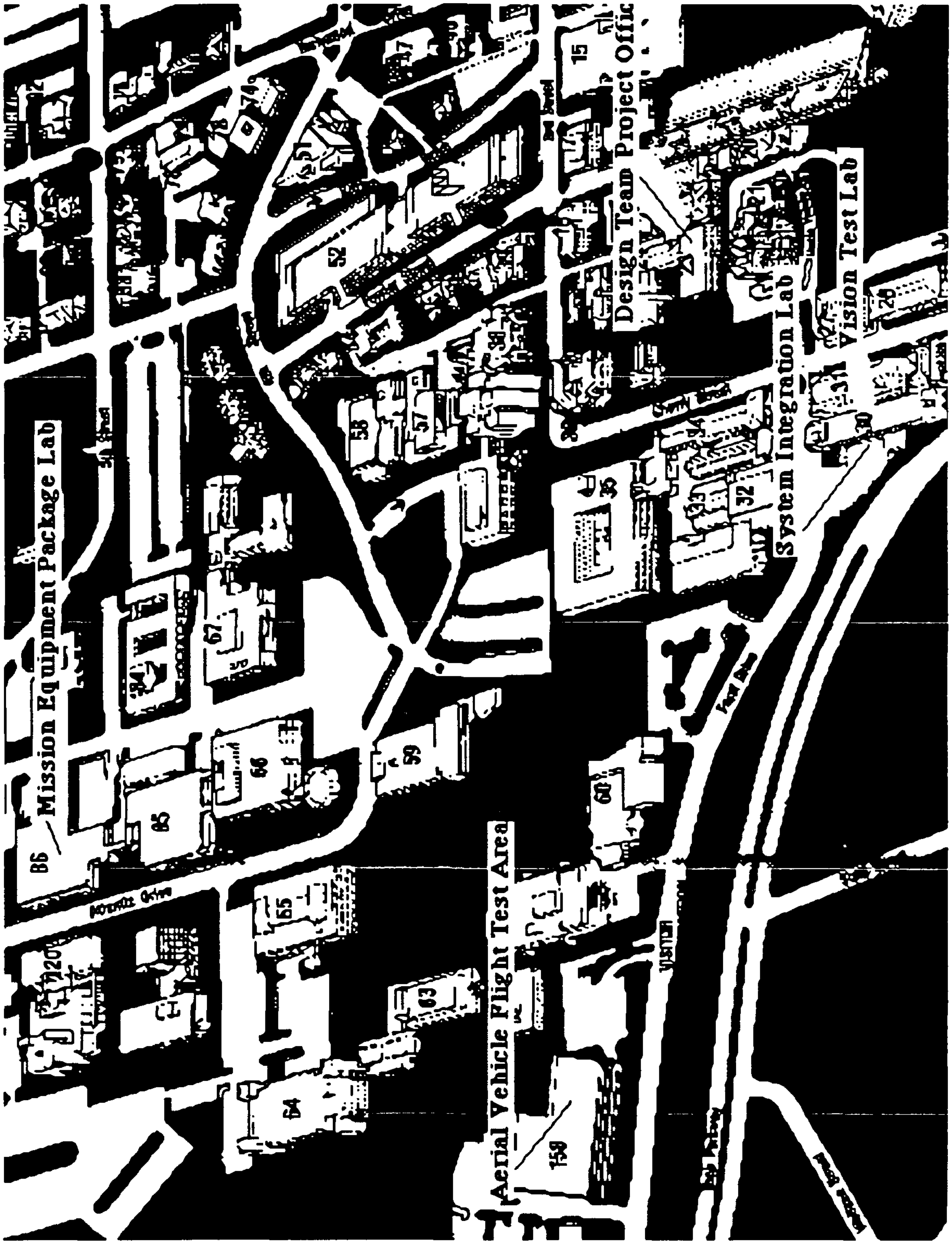


Figure 12 - Allocated Floor Space vs. Time



1" = approximately .1 miles

Figure 13 - Aerial Robotics Facilities

However, as design applications are a focus of both undergraduate and graduate programs in most engineering schools at Georgia Tech, the team did possess considerable knowledge of the design process, although limited experience beyond the preliminary design stage.

Why Were Concurrent Engineering Techniques Important to this Project?

In order to counteract effects of the radically-shortened design cycle presented by the AUVS and limited budget, techniques to reduce development time and achieve higher quality at lower cost were necessary. These principles are the underlying emphasis of concurrent engineering application[12].

The original intent of the Institute for Defense Analyses (IDA) study [1] (Winner) in evaluation concurrent engineering applications was to prove or disprove the claim of shortened design cycles resulting in higher quality products with lower life cycle costs. Winner's report documents several examples of proven application of CE principles throughout industry. More recently:

- Development of an integrated computer-aided design (CAD) and manufacturing environment (CAM) at Lockheed during their recent successful Advanced Tactical Fighter (ATF) bid, resulted in fewer than 200 engineering design changes being required during assembly of the first aircraft [6].

- Simulation applications by the U.S. Army Tank-Automotive Command (TACOM) Research Development, and Engineering Center resulted in: (1) improved product performance through the ability to investigate a variety of design alternatives prior to the

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12. Daniel P. Schrage, "Preliminary Design of a Light Commercial Utility Helicopter", Concurrent Design: A Case Study, p. 8.

prototype stage, (2) reduced design and manufacturing costs through identifying and solving mechanical problems during the design phase, (3) and the ability to select a more economical design alternative with equivalent performance [7].

If the documented gains through application of concurrent engineering techniques were not enough, Sobieski [8] argued the traditional sequential design process results in suboptimality in design. Given that resources, as described in the previous section, are limited, Sobieski asserts that optimization loops on the sequential design process [Figure 14] are impossible. This suboptimality results in, what Sobieski terms as, "the Paradox of Sequential Design" [Figure 15]. As knowledge about the design increases, the engineer's ability to influence the design, based on that knowledge, is reduced.

Schrage and Rogan [9] qualitatively address the impact of concurrent engineering's application to this 'paradox'. Given that product and process are engineered concurrently, greater knowledge is available earlier in the design cycle when design freedom is still high [Figure 16].

In the aerial robotics competition context, application of concurrent engineering techniques, documented to have reduced product development cycles by as much as fifty (50) percent[13], could theoretically result in 'stretching' the robot's development time to over 514 design days. Fewer design changes would ultimately result in lower development cost, desirable given the product was initiated with an uncertain monetary foundation.

13. Winner et al., p. vi.

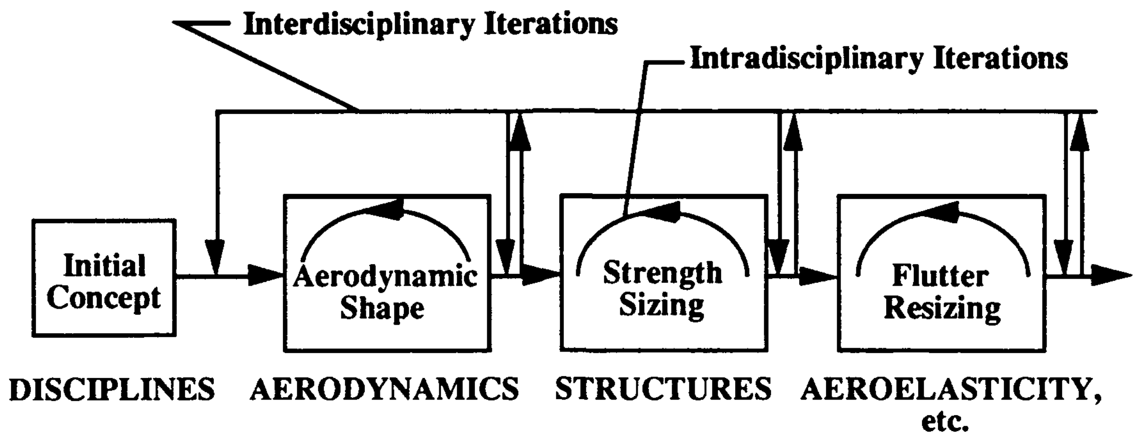

Figure 14 - An Example of the Sequential Design Process[14]

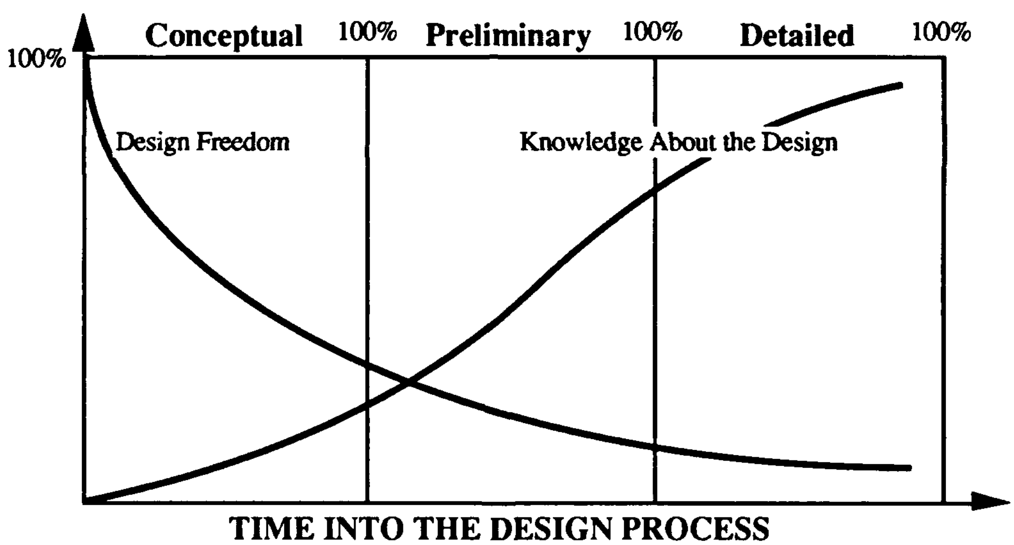

Figure 15 - "The Paradox of Sequential Design"[15]

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14. Jaroslaw Sobieszczanski-Sobieski, "Multidisciplinary Optimization for Engineering Systems: Achievements and Potential", Lecture Notes in Engineering, Proceedings of an International Seminar Organized by Deutsche Forschungsanstalt fur Luft- und Ramfahrt (DLR), Bonn, June 1989, p. 43.

15. Ibid., p. 45.

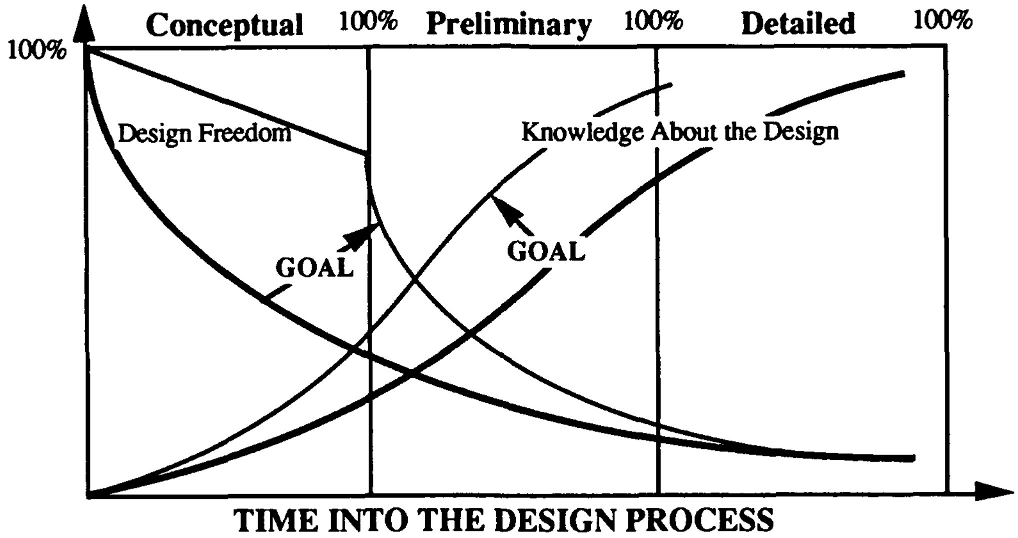

Figure 16 - Impact of Concurrent Engineering Application[16]

* NOTE: Conceptual, preliminary, and detailed, as noted in the figures above, describe typical periods of the sequential design cycle.

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16. Daniel P. Schrage and J. Edward Rogan, "The Impact of Concurrent Engineering on Aerospace Systems Design", White Paper, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, p. 6.

CHAPTER II

HOW WAS CONCURRENT ENGINEERING TO BE IMPLEMENTED?

Ten Characteristics Required for the Successful Implementation of Concurrent Engineering

In an effort to capture lessons learned by various companies, the Computer-Aided Acquisition and Logistics Support (CALS)/CE Mechanical Systems Working Group highlighted ten characteristics identified as keys to successful implementation of concurrent engineering [5]. Schrage [10] further modified this list to include *prerequisites* for their implementation.

The Georgia Tech Aerial Robotics Design Team adopted these tenets as a template for their group's organization and design policies and procedures. A discussion of how these characteristics were to be put into practice follows.

A Top-Down Design Approach Based on a Comprehensive Systems Engineering Process.

Top-down design implies an evaluation and decomposition of the perceived design task into smaller engineering problems and is a common design method across several engineering fields.

MIL-STD-499A [11] defined systems engineering (SE), in the Department of Defense (DoD) context, as:

> the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total maintainability, safety, survivability, human, and other such factors into the total engineering effort to meet cost, schedule, and technical performance objectives[17].

Top-down design, on its own, stands the chance of decomposing the problem into a myriad of specialty-specific 'sub-solutions'. Systems engineering manages these to ensure an integrated team effort to meet design objectives specified in the SE definition itself.

Successful concurrent engineering requires a combination of both participative and authoritative management[18]. Participation of all specialties in the design solution is imperative to consensus building and establishing a sense of ownership about the design. In some cases however, specialty-specific design solutions do not contain the appropriate global perspective and require authoritative adjudication.

Implementation of this tenet in design of the GT aerial robot was accomplished through implementation of a Work Breakdown Structure (WBS) and development of a System Engineering Management Plan (SEMP).

A WBS was developed to component level. Responsibility for design of the system's various pieces was then assigned using this structure. The WBS was also helpful

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17. Defense Systems Management College, p. 1.2.

18. Daniel P. Schrage, Concurrent Design: A Case Study, p. 10.

in identifying specialties not represented on the team and provided a 'wish list' for prospective team members.

The SEMP was modeled after the Joint Project Office's (JPO) Unmanned Aerial Vehicle (UAV) System Engineering Management Plan [12] issued by the DoD. A common language to describe system components, team organization and responsibilities, a projected milestone list, and team management philosophy were included.

Electronic correspondence, utilizing the Georgia Tech campus computer system, was implemented. This allowed student engineers the ability to communicate rapidly and securely with the entire team through use of the subscriber group *uav@pravda*. Communication between individuals could be accomplished using normal e-mail procedures. E-mail was deemed particularly important given the multidisciplinary, hence dispersed-about-campus team. It further served as a historical record, through default means, of the design process.

Strong Interface with the Customer.

Taguchi defines quality as "the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions"[19]. Understanding what society (the customer) wants, therefore, is key.

The team clearly identified the customer for this product as the Association for Unmanned Vehicle Systems (AUVS) with the competition rules and updates serving as their Request for Proposal (RFP) or Product Definition Specification (PDS). Satisfying these requirements would likely result in a quality, and ultimately winning, system. Customer requirements were further analyzed through Quality Function Deployment

19. Genichi Taguchi, "The Evaluation of Quality", p. 1.

(QFD) tables. This study was the focus of several student teams in a Concurrent Engineering project accomplished to compliment preliminary system design by Georgia Tech's aerial robotics team.

The system engineer was designated primary point of contact for the team with the AUVS. This was done in order to assure all questions were focused through a single voice and that answers received were disseminated to the entire team.

Multifunctional and Multidisciplinary Teams.

Schrage describes this as the "characteristic most associated with concurrent engineering"[20].

As already discussed in outlining the team's design environment and in describing work responsibilities, specialties were sought which would contribute to the system's overall design.

Obvious during initial organization meetings was the requirement for computer, electrical, and mechanical, as well as aerospace engineers. Ultimately, students from these engineering schools and the School of Civil Engineering participated on the design team. Faculty advisors, as diverse in technical specialties, complimented the student contingent and provided expert advice in application of various technologies to the system.

Design Benchmarking and Soft Prototyping.

Design benchmarking implies continual comparison of one company's competing design to another's. This provides some measure of design quality, but used alone, can result in an incrementally better system to another competitor, while a vastly superior design may have been possible.

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20. Daniel P. Schrage, Concurrent Design: A Case Study, p. 12.

Soft prototyping requires the development of a digital product model[21]. This results in tremendous savings of both time and funds, as described in the example of TACOM's simulation successes.

When combined with benchmarking, soft prototyping allows comparison of digital prototypes to competitor designs without huge resource expenditure. Design freedom is thus maintained to explore other, perhaps better options.

Although the AUVS did not distribute details on competitor progress leading up to the competition, and teams, for the most part, elected to maintain some degree of secrecy about their designs, benchmarking, as a means to define the system's configuration at a specific point in the design cycle, was done. The team published a Benchmark 1 report, describing the aerial robot's preliminary design. This document was provided to the customer and the team's industrial partners.

Soft prototyping efforts were initiated through development of a computer solid model of the system's payload and through computer-aided design (CAD) application to magnetic array layout. The solid model's database ultimately provided required dimensions for the forward payload shelf, several universal joint (u-joint) components, electrical connections, and greatly assisted with weight and balance efforts. CAD application to the magnetic array resulted in a geometrically optimized layout and reduced the originally suggested magnet number by 33% with no performance penalty.

Simulation of Product Performance and Manufacturing and Support Processes.

The team envisioned applying several widely-used computer design tools. As examples, ARMCOP, a stability and control simulation package developed by NASA, was to evaluate stability and control characteristics of the aerial

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21. Daniel P. Schrage, Concurrent Design: A Case Study, p. 13.

vehicle under different weight and balance configurations. Various commercially-available digital circuit board simulation and layout tools were readily available.

The design team was unaware of any tools available at Georgia Tech which could simulate the manufacturing or support processes, although such tools exist. As an example, as part of its Integrated Product Development (IPD) initiatives, General Dynamics Fort Worth developed COMOK (Computerized Mock-Up) which, when coupled with the "electronic crew-chief", allowed engineers the ability to study maintainability issues through simulation, eliminating the need for hard mock-ups [13].

Early Involvement of Subcontractors and Vendors.

During the system's conceptual design phase, the team hosted an overview for interested representatives from industry. From this point, and continuing throughout the design cycle, periodic site visits by off-campus team participants kept everyone aware of the system's progress, as well as providing necessary feedback. As already mentioned, the Benchmark 1 report was provided all team participants and equipment donors as a means of keeping communications with team supporters open.

Although the number of vendors providing components to Tech's aerial robot was significantly less than with commercially-produced aircraft systems, it was felt that common agreement on scheduling objectives through adoption of an integrated schedule might alleviate integration conflicts downstream.

Results of the team's partnership efforts have resulted in relationships extending into the next design phase.

Continuity of the Teams.

The team, in its preliminary effort, could not hope to accomplish this longer-term objective. However, some attention was devoted to ensuring a balance of undergraduate and graduate student participation in order to maintain a team over the next several years.

Practical Engineering Optimization of Product and Process Characteristics.

The team's initial goals were simply to design and develop a baseline system. Should time be available, within the constrained design cycle and, after successful demonstration of this system accomplishing the AUVS mission, product optimization could be attempted. Process optimization, like team continuity, was something to be addressed after progression through at least one complete design cycle.

Optimization focus, should the team progress that far, was addressed to a limited extent in the integrated schedule and the Benchmark 1 report.

Experiments to Confirm/Change High Risk Predictions Found Through Simulation.

Simulation efforts were limited during this initial phase due, primarily, to time necessary to set up an appropriate simulation environment. In addition, quality engineering experiments typically rely on historical statistical information on which to base engineering experiments. This type data was simply not available due to the uniqueness presented by design of a system on this scale.

The tenth characteristic of successful CE implementation, Corporate Focus on Continuous Improvement and Lessons Learned, has been deferred more appropriately to the Analysis of Results and Conclusions sections of this report. It was, however, recognized that documentation would serve a significant function in eventual team success, either during the first, or a successive, competition. To that end, files of meeting agendas, design discussion, expenditures, and other relevant information were kept. The completeness of this thesis, and other post-Phase I documents, is ultimately a measure of the team's attention to record-keeping while the team's competition performance over time will serve as an adequate metric of success in applying this tenet of concurrent engineering.

CHAPTER III

THE AERIAL ROBOT DESIGN CYCLE

Overview

Work to develop the Georgia Tech aerial robot was, except for the period immediately preceding the competition, accomplished in three month blocks. Four discrete time elements, coinciding with the quarter class schedule and comprising the design cycle, are presented here.

Block 1	August - December 1990
Block 2	January - March 1991
Block 3	April - June 1991
Block 4	June - July 1991

Presentation in each block will attempt to overview the design environment by reviewing significant changes in team resources, listing cumulative assumptions bearing on the problem which have not been eliminated through hardware selection or component testing, highlighting important information gained about the design, and, where appropriate, outlining design objectives for the period. Work accomplished will be

reviewed, including quality engineering tools and concurrent/systems engineering concepts which supported design decisions. Finally, a brief recap of the project's status at the close of each time phase will be given.

Block 1 (August to December 1990) Establishing the Design Environment, Problem Definition, and Aerial Vehicle Selection

The Beginning.

A joint meeting between interested students and faculty and the Association for Unmanned Vehicle Systems (AUVS) was held in late-August in the School of Aerospace Engineering. Interested faculty in attendance included professors from the Schools of Aerospace and Civil Engineering. The AUVS was represented by Mr. Robert C. Michelson, First Vice-President and author of the First International Aerial Robotics Competition. The primary focus of this gathering was to review proposed rules for the competition and to discuss formation of a Georgia Tech team.

This working group determined the competition would provide a unique opportunity to field a multidiscipinary design team. Academic courses were envisioned to compliment required design tasks, and formulation of the design as a concurrent engineering pilot project, which Winner had found useful in demonstrating CE benefits[22], began.

Funding was presented as a key issue. Similar hardware-oriented engineering competitions had proven extremely expensive in the past.

Finally, the group recognized the challenge presented by a July 1991 competition date. The system's underlying assumption, that *insufficient time was available in which to*

22. Winner et al., p. 48.

design an aerial vehicle and that a commercially-available system should be procured, was made at this initial meeting.

Organizing the Team using a Work Breakdown Structure.

Throughout the remainder of the Block 1, a series of team 'recruitment' meetings were held. Invitations were made to faculty and staff members in the Schools of Aerospace, Civil, Mechanical, and Electrical; the College of Computing; and the Georgia Tech Research Institute (GTRI). In particular, individuals with demonstrated expertise in autonomous robotics, control system engineering, sensor engineering and manufacture, and design were invited to these preliminary meetings. It was felt that research already underway by each of these professors and their graduate students might be of assistance to, and simultaneously enhanced by, work on this project.

The first of these meetings was held on September 28th. During this meeting, Dr. Daniel Schrage presented an overview of a long-term concurrent engineering pilot project to be centered around development of the autonomous aerial robot. Phase I was organized to focus on development of the robot for the AUVS competition-specific function. A follow-on phase, to be accomplished after successful performance in the Aerial Robotics Competition, was to conduct detailed research on specific components, technologies, and methodologies which might be served by the aerial vehicle as a test bed. Attendees included students from aerospace, electrical, and computing backgrounds.

The 'team' was directed to develop a Work Breakdown Structure (WBS) to Level 4. This would help assign responsibility within the system, as well as to evaluate technical specialties needed, but not yet available within the group. A WBS presented in the UAV SEMP drafted for the JPO was to be used as a model.

A hierarchical decomposition of "hardware, software, services, and data which completely defines the problem"[23], the WBS is essential to identifying the product to be engineered and relates elements to one another and the system.

Communication. In addition to WBS-development efforts, students discussed methods to enhance communication between design team members. A computer bulletin board, with a database of parameters describing each hardware component, was debated. The intent of this tool was to allow any student immediate access to all technical data involved with the design. With this continuous update, evaluation of changing parameters and their effects on the design and manufacture of other subsystems could be identified, then addressed through communication on the more traditional e-mail network. Implementation required each subsystem to develop a list of technical information which would describe that component in words.

While an e-mail subscriber group was eventually established, the bulletin board, as described here, was never accomplished despite renewed efforts during Block 2. Use of the e-mail subscriber group, however, did allow communication between any member of the design team and another, bypassing more rigid lines of coordination that sometimes stall idea exchange.

On October 12th, the first scheduled bi-weekly working group meeting was held. Faculty from the School of Electrical Engineering and the College of Computing joined the effort. The initial WBS was presented [Figure 17]. Responsibility for development of each subsystem was divided among the represented engineering schools and colleges. An attempt was made to align perceived technical requirements of the subsystem, as described by the WBS, to school-specific engineering specialties. Aerial vehicle development was,

23. Defense Systems Management College, p. 9.1.

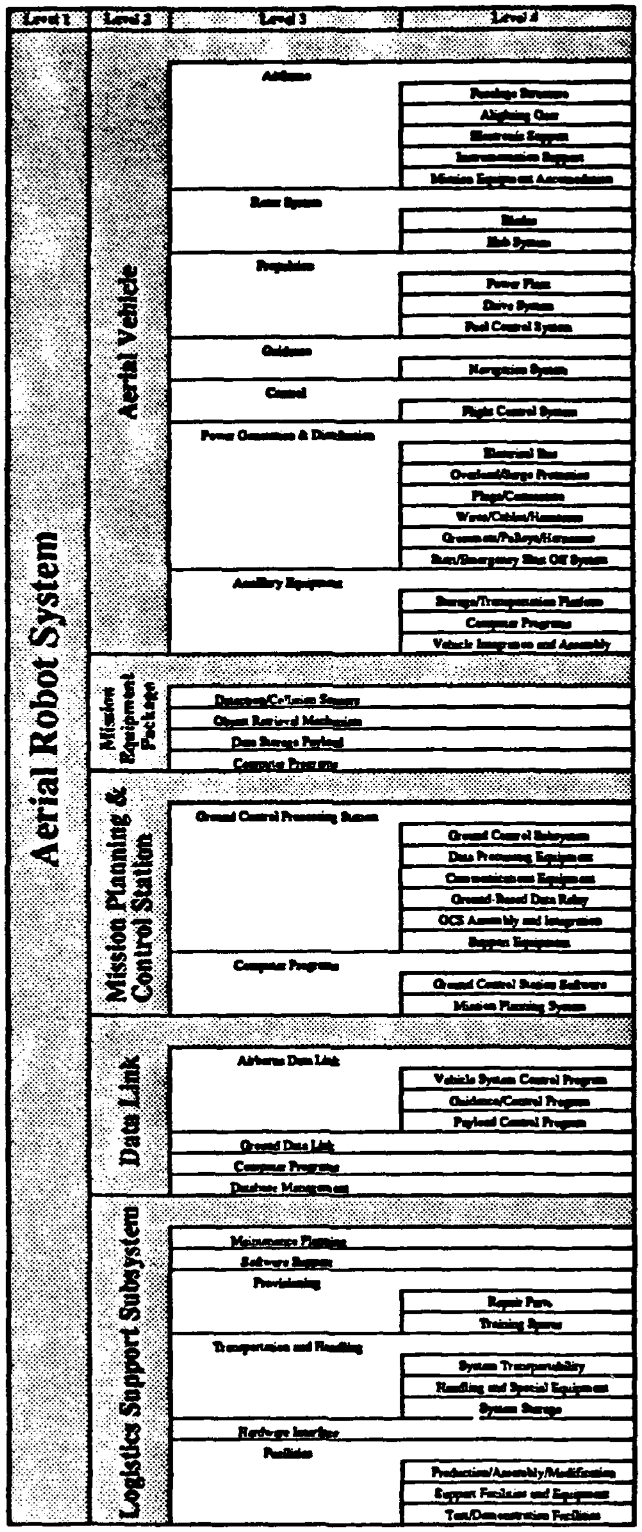

Figure 17 - Preliminary Work Breakdown Structure

therefore, assigned to the aerospace school and development of the mission planning and control station (ground control), given to the College of Computing.

Nomenclature common to the UAV SEMP was selected to describe the subsystems. As industrial partners were soon to be pursued, and the DoD had been involved with industry for several years using these terms, use by the Georgia Tech team was seen as a way to enhance communication with prospective supporters.

In order that each subsystem group understand their design requirements, draft of a team SEMP, similar to the DoD document, was required.

Given the absence of such a document, team members began market studies of hardware components applicable to the project. In addition, 'excess' school equipment was identified for use in an effort to further reduce the effort's cost. Market studies of available aerial vehicles, microprocessors, and communication components were initiated.

'Brainstorming' sessions attempted to evaluate vehicle alternatives and system sensor requirements. Although subsystem design 'boundaries' had already been established, this relatively 'unfocused' activity ensured the system captured the combined experience offered by the multidisciplinary team.

Aerial Vehicle Market Evaluations.

Until payload weight and volume, achievable on an aerial vehicle of the size dictated by the competition, was fully understood, market evaluations and brainstorming sessions could not narrow focus to discussion of feasible hardware and methodology alternatives. In fact, Pugh [14] presented references which indicate that when random brainstorming is accomplished, it is of little utility. "...The more specific the context, the more prolific and useful the solutions"[24]. With this in mind, the aerial vehicle group initiated a detailed market study of commercially-advertised systems in mid-October.

While over twenty helicopter, ducted-fan, and co-axial vertical takeoff and landing (VTOL) aircraft were actively being marketed, only a handful of these designs had progressed beyond the prototype stage.

Competition rules restricted arena access to two team members. Therefore, a system capable of being lifted and carried by two men was adopted as an informal gross weight limit. It should be noted here that selection of one particular system from those surveyed was not the goal of this exercise. On the contrary, only a reasonable guess as to how much payload weight may be offered by a given sized aerial vehicle was the analysis' objective.

Given the data available, it was estimated that a minimum of twenty-five pounds of useful load (fuel and payload) might be offered by a 100-pound aircraft [Figure 18]. Twenty-five pounds was considered more than adequate by computer and electrical engineers then involved with the project.

A Block 1 goal of aerial vehicle selection was established.

The maturity of ML Aviation's co-axial *Sprite* and usable weight fraction of thirty (30) percent, made it an attractive option. ML Aviation was approached, but felt their overseas location (Great Britain) made affiliation with a United States team impractical.

As the competition mission profile only required flight at very low airspeeds and significant hover times, a VTOL configuration with high hover efficiency (high thrust with low disk loading) [Figure 19] was desired. With the best co-axial option gone, a more focused effort toward identification of a feasible helicopter design was begun.

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24. Stuart Pugh, Total Design: Integrated Methods for Successful Product Engineering, Addison-Wesley Publishing Company, Wokingham, England, 1990, p. 90.

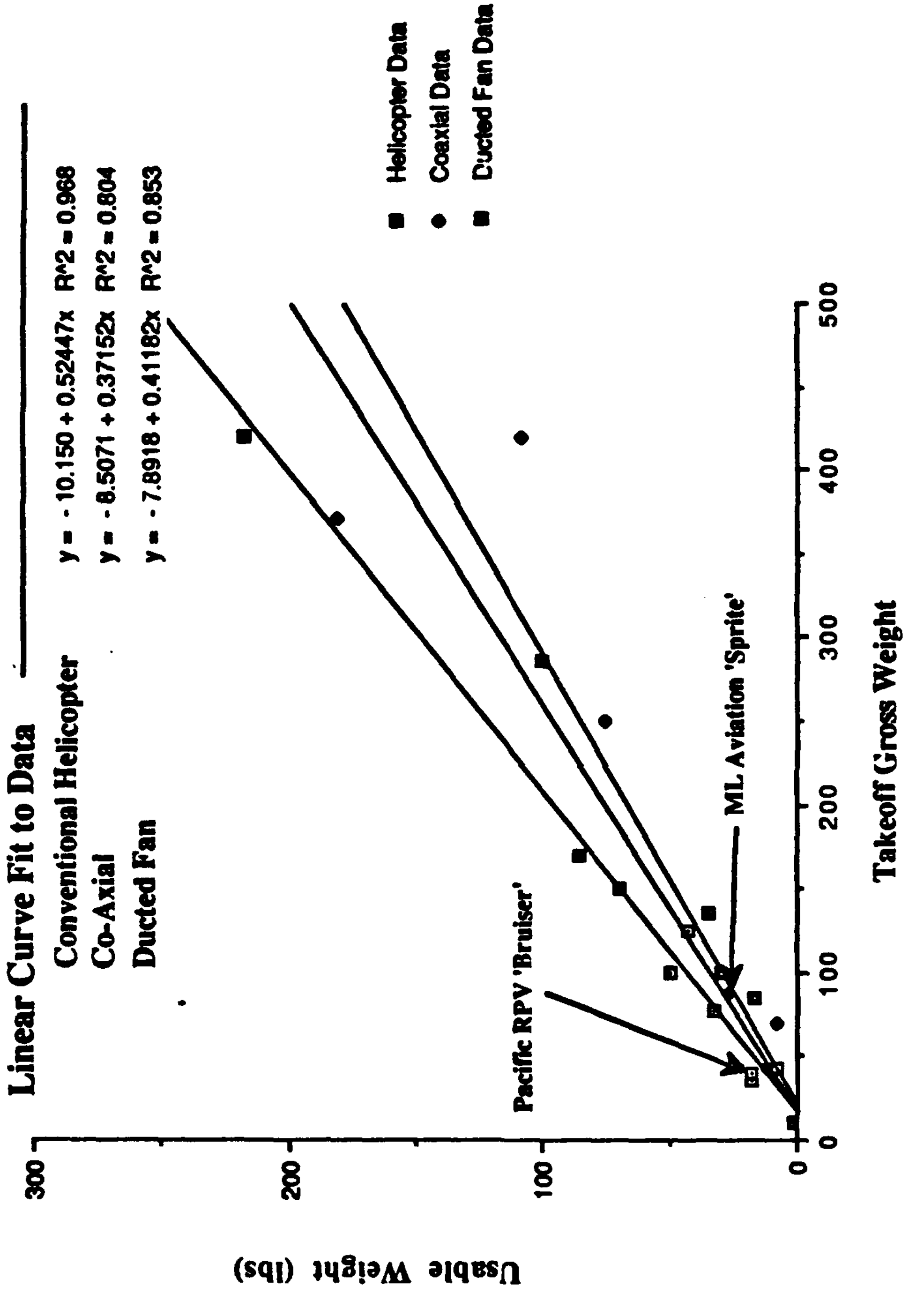

Figure 18 - Usable vs. Takeoff Gross Weight of Candidate Aerial Vehicles

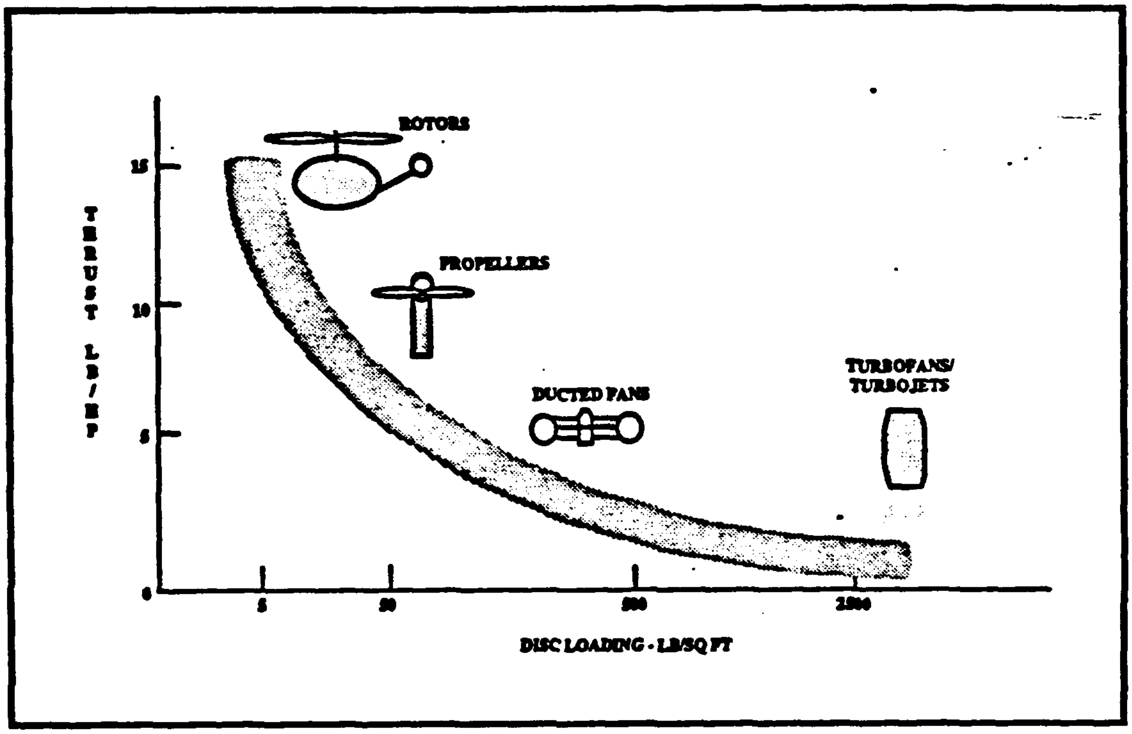

Figure 19 - Hover Efficiency of Various VTOL Configurations

Industrial Sponsorship.

Concurrent with evaluations of candidate hardware was the effort to identify potential team sponsors. It was hoped that through solicitations to companies already involved in the unmanned aerial vehicle market, both hardware and expertise might be offered the team through partnership.

Over sixty corporations, business, laboratories, and individuals were notified of the effort at Tech and asked to respond by November 9th to an invitation to be briefed on the team's progress in Atlanta. Key invitees were those the team perceived to have high-dollar hardware components applicable to development of this system.

Representatives from Boeing Helicopter, Rockwell, United Technologies, the United States Army Aerostructures Directorate, and Signal Tree Research attended a day-

long conference on November 15th. Of the five organizations represented, only the Army Aerostructures Directorate would ultimately team with Georgia Tech.

Team Growth Continues. Continued recruitment through electronic bulletin board announcements and personal invitations resulted in increased student participation by computer and civil engineers. Although involved in many of the early organizational meetings, the civil engineering contingent was formally assigned responsibility for data link development in early November.

The System Engineering Management Plan (SEMP).

A SEMP [14] covering the Tech team's efforts was published in mid-October and distributed to the team on November 9th. The document outlined organization of the team, management philosophy, responsibilities for work within the system, a proposed schedule/milestone list, and description of system components. Key in this document were definition of various terms used by the team in describing system pieces.

The SEMP established the following design objectives:

(1) by the end of Winter quarter 1991, to have identified, purchased, and completed component-specific engineering necessary to begin integration.

(2) during Spring quarter 1991, to integrate the subsystems into a working system.

(3) during Summer quarter 1991, to accomplish detailed testing and, where appropriate, optimization of the system.

In general, the System Engineering Management Plan's "principle role is in identifying and assuring the control of the overall engineering process"[25]. It was hoped the Tech document would adequately serve a similar purpose.

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25. Defense Systems Management College, p. 3.1.

Selection of the Pacific RPV *Bruiser*.

By mid-November, aerial vehicle options had narrowed to two competing helicopter designs, although both exceeded the six foot size restriction imposed by competition rules.

Conversations with both aircraft manufacturers highlighted Pacific RPV's ability to modify their existing Bruiser airframe to meet size constraints. Further, this aircraft was being procured by the United States Army Aerostructures Directorate for use in their Free-Flight Rotorcraft Research Vehicle (FFRRV) project [15]. In addition, the Naval Postgraduate School had utilized two of these aircraft in research accomplished there. Similar hardware capabilities as these two research institutions was an attractive long-term feature of the Bruiser's selection.

A modified Bruiser II aircraft [Figure 20] was ordered on November 19th. Manufacture was anticipated to take approximately three weeks with delivery to the Tech team to take place shortly after classes began in January 1991.

A stability augmentation system (SAS), developed for one of Pacific's larger model aircraft, was also applicable to the Bruiser and was configured to interface readily with available hobby control systems. Algorithms developed for the SAS were advertised to be "readily ported to a larger, more sophisticated control system that incorporates auto-pilot functions and autonomous operations". Although not initially purchased, further evaluation of the SAS, seemed warranted.

In addition, Pacific agreed to provide the team a .60 series *GMP Competitor* to be used as a flight trainer.

Block 1 Wrap Up.

A final Fall quarter meeting was conducted on December 4th.

Team Contact with Local Radio-Control Modelers. Due primarily to selection of the Bruiser as the team's aerial vehicle, contact was established with several local radio-control (R/C) modelers. Two members of the Cobb County Radio-Control Club (CCRC), attended this December 4th meeting.

The team's intent was to utilize these experienced modelers to help train one or more student pilots. A by-product of this contact was an extremely rapid learning curve progression through key R/C operation and maintainability issues. This relationship would prove crucial in the coming months.

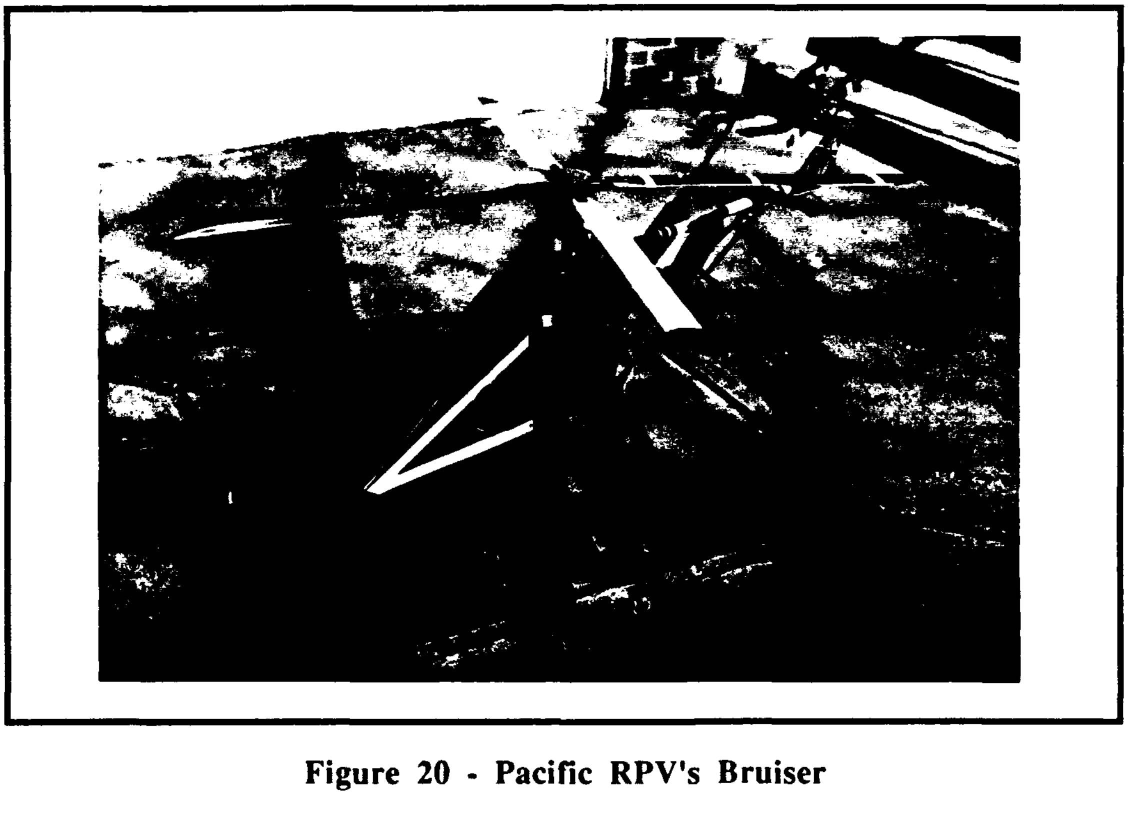


Figure 20 - Pacific RPV's Bruiser

Student Participation. At the Fall quarter's conclusion, only the aerial vehicle, mission planning and control station (MPCS), and data link were 'covered' by student leaders. Although two faculty members of the electrical engineering school had participated throughout the quarter, only one student had become involved, leaving significant work to be done in design and manufacture of the disk retrieval system.

Less significant, due to the status of procured hardware, but no less important, was a manpower void in the system's logistics support structure. Arrival of the Bruiser would necessarily require growing attention to maintenance and other logistics issues.

Faculty Participation. All major subsystem groups, less the logistics support subsystem, were supervised by team faculty advisors at the conclusion of the Fall quarter. Even with the already large faculty contingent, no mechanical engineering professors were yet involved with the team.

Industry Partners. In addition to Pacific RPV, Incorporated, Guided Systems Technologies (GST), a small company located in Georgia Tech's Advanced Technology Development Center (ATDC), had become involved. With particular expertise in control system design, it was hoped GST could assist the team in design of their autonomous flight control system.

In a conference call with Pacific RPV following this final meeting, discussions of vehicle stability yielded projected attitude hold within .1 degree and heading to within 1 degree. Further evaluation of the costs involved in procuring one of Pacific's stability augmentation systems resulted in an expected $1200 to $1300 expenditure were the boards laid out at Pacific and manufactured at Georgia Tech, a substantial cost savings to the team.

Knowledge About the Design.

Assumptions.

(1) The underlying assumption for development of the entire system was the evaluation that insufficient time would be available to manufacture an aerial vehicle 'in-house'.

(2) Any discussion of computer vision as applied to development of this system centered around application of the Dickerson integrated vision system (IVS). Details of the system are provided at Appendix A.

(3) The team felt that retrieving six disks was an attainable goal.

Competition Rules. Nearly three months of evaluation resulted in a clear picture of the competition's requirements. Where uncertainties existed, proximity of the team to the event's author resulted in rapid resolution.

System Hardware. While the aerial vehicle had been selected, only scant marketing data and information gained from telephone conversations with the aircraft's manufacturer were available. Final aircraft dimensions were still to be determined during manufacture.

Other Bruisers had been shown to lift approximately eighteen (18) pounds of payload.

System Software. Although a very preliminary effort, top-down decomposition of required mission planning and control tasks was accomplished. Key system issues regarding power up and component initialization procedures began to be addressed.

Design Freedom.

In the context of this thesis, available design freedom was viewed as unspent capital resources. Therefore, purchase of the Bruiser aircraft resulted in a loss of approximately 35% of the team's freedom about the design. A more detailed evaluation of this trend is offered in the Analysis of Results.

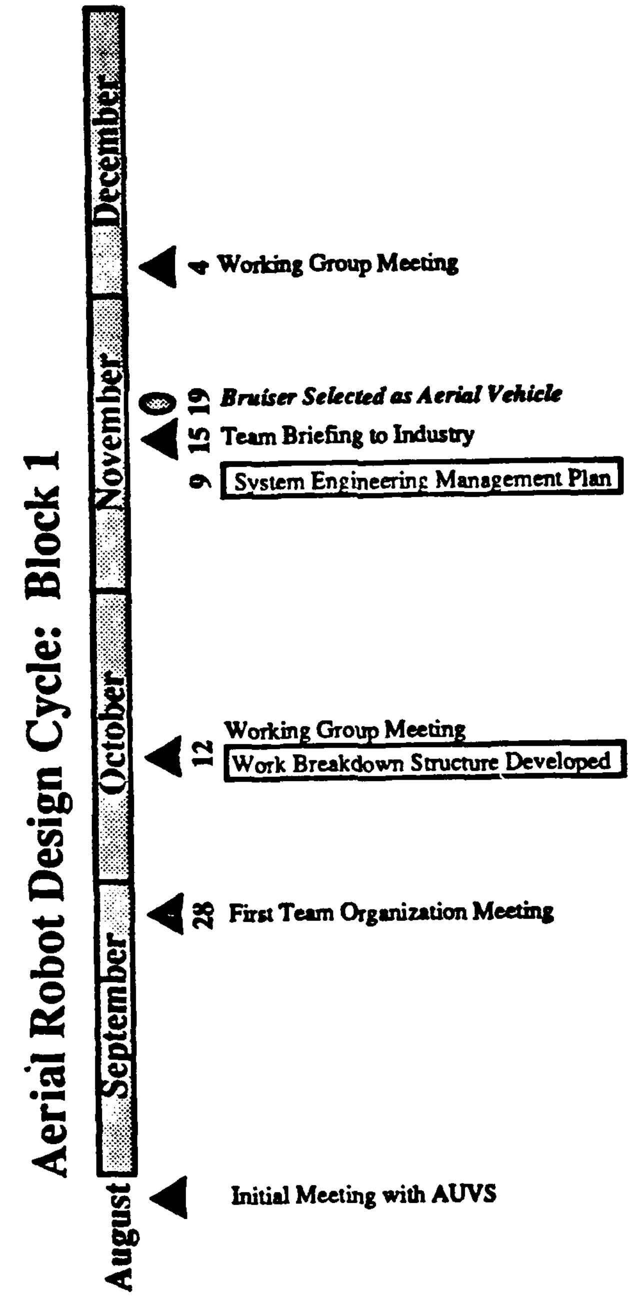


Figure 21 - Key Block 1 Design/Organization Events

Block 2 (January to March 1991)
Refining the Design Environment and System Definition

Design Environment Overview.

Time. Roughly sixty percent of the available design cycle (206 days) remained with commencement of classes in early January.

Continued Student Recruitment. With delivery of the aerial vehicle pending, and receipt of additional funds to support the project, concerted efforts were initiated to round out the student design team contingent.

With the assistance of the CCRC, an R/C helicopter demonstration was scheduled adjacent to the Student Center on January 4th in order to attract attention to the competition and Georgia Tech's efforts. In particular, electrical and mechanical engineering students were sought to assist with key disk retrieval and vision issues. High winds, however, forced cancellation of the event.

A final organized appeal for support was made four days after receipt of the Bruiser on January 7th. Mr. John Smith of Pacific RPV, principle aircraft designer and manufacturer, visited Georgia Tech in order to personally hand off the aircraft and address team questions. His comments attracted a large student audience as he described the Bruiser's development and current commercial applications. This gathering, and the supporting curriculum to be described, resulted in student participation reaching a peak of near twenty-five (25) graduate and undergraduate engineers.

Supporting Academic Coursework. In addition to direct recruitment efforts, several courses, taught by faculty involved in the aerial robotics effort, addressed system issues through application of course projects to the design. This type support, unique to an academic environment, while not directly providing manpower resources to the system's

design, was a useful tool in leveraging team manpower to more mainstream design alternatives.

A concurrent engineering course, utilizing the aerial robotics design effort as a project focus, further analyzed the competition requirements and sought to establish a preliminary design through detailed system synthesis using quality and system engineering techniques.

Electrical engineering coursework on the manufacture of sensors and transducers led directly to development of the system's altimeter and object retrieval mechanism.

Evaluation of the vehicle's stability and control characteristics was accomplished as the quarter project by a helicopter stability and control course.

Finally, a myriad of special topics and problems addressed a variety of system issues beginning in the Winter quarter 1991, and continuing through the competition's completion. For example, two electrical engineering design problems addressed an autonomous ground robot as an alternative to development of a vehicle-nested retriever.

Faculty Involvement. All discussion of computer vision as applied to this design had centered around use of a lightweight integrated vision system developed by Dr. Steve Dickerson in the School of Mechanical Engineering. His formal involvement, beginning in early January, would serve the team as a needed information resource as the camera matured in both hardware and computer-code toward specific application in this context.

Industrial/Government Participation. In early February, the Aerostructures Directorate formally joined the team. Their expertise with data link options and electronic component development would prove crucial in the final weeks leading to the competition.

Community Interaction. The team made a formal presentation to the CCRC on January 21st. This meeting produced a machinist volunteer and resulted in a discount being offered the team to purchase R/C supplies at a local hobby shop.

Budget. Significant funding through joint research seed monies was received in early January. This, and the grant already obtained through the Office of Interdisciplinary Research in mid-November, represented 96.7% of the capital available for system development. A final request to the Georgia Tech Student Foundation on February 17th was not granted as they perceived the aerial robotics effort capable of attracting sufficient outside resources.

Facilities. An additional bay in Room 103 of the Montgomery Knight building was obtained in early-January.

Initial Executive Committee (EXCOM) Meeting.

Work during the Winter quarter began with receipt of the Bruiser aircraft on January 7th. Assembly was quickly accomplished, but no further evaluation was conducted, pending a visit by the aircraft's manufacturer later that week.

The EXCOM, as defined in the SEMP, met for the first time officially on January 9th. The following team and design issues were discussed at that meeting:

Team Reorganization. Perceived 'excess' team members in the aerial vehicle group were reassigned responsibility for the integrated logistics support subsystem. As the aircraft would quickly represent the thrust of that effort, use of an aerospace engineer to fill this team void seemed logical. No technical expertise was, however, available in any of the subsystems which would allow development of a retriever to be initiated. Therefore, openings were still recognized in the mission equipment package and, because of only three undergraduate students participating, the data link subsystems.

A vision group, led by students from the College of Computing, was formed to address hardware and software development of the Dickerson camera. At this stage, only one camera was to be used to perform both the navigation and target detection functions. It

was hoped the 'switching' problem between function-specific optics and algorithms would be solved by this group.

Flight Training to Commence. A volunteer from the CCRC agreed to offer a ground school to students interested in learning how to fly R/C helicopters. A commercially-available flight simulation package was loaned, and another purchased for use at Tech.

Aircraft Test Scheduling. As team focus centered on gathering as much technical information about the aircraft as quickly as possible, scheduling issues needed to be addressed. The aerial vehicle group was directed to develop a test schedule with input from the other subsystems.

Payload Areas. Two payload areas were obvious, one forward of the firewall and another underneath the keel plate between the landing gear [Figure 22]. It was decided the forward area would be reserved for all hardware associated with the data link, guidance system, and flight control computers.

The lower payload area was designated for use by the mission equipment package (MEP). As the retriever was anticipated to be one of the heavier payload components, its placement as close to the main rotor mast as possible was critical. In addition, desired 'placement' of the longitudinal center of gravity could then be accomplished through subtle displacement of the retriever along the vehicle x-axis.

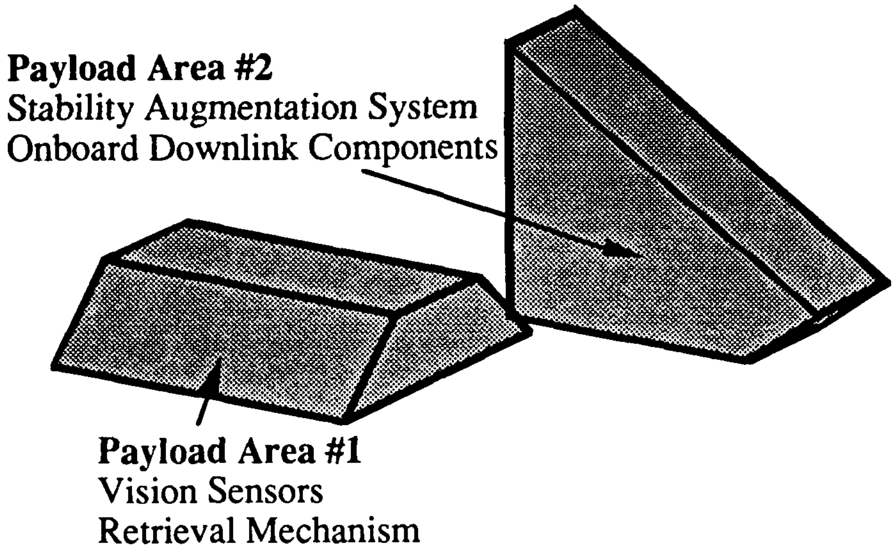


Figure 22 - Designated Payload Areas

A preliminary design freeze, anticipated at the end of work for the Winter quarter, was hoped to identify volume and weight issues associated with payload layout. Some modifications to the existing landing gear (addition of a payload shelf) and forward payload fairing (increase volume) were envisioned.

Assumptions. It was recognized that design work being accomplished in the various courses already mentioned needed some technical constraints. Therefore, the system engineer presented a series of assumptions about the design which he hoped would further focus conceptual and preliminary design efforts.

(1) Vehicle dynamics were considered too fast for data link to ground-based computers for control. This assumption was made after several telephone conversations with the aircraft manufacturer and analysis of the system's vulnerability through use of offboard computing power. The impact of this assumption was that computational capability necessary to stabilize the aircraft must be onboard.

(2) The aerial vehicle was assumed capable of holding position to plus or minus three inches (3") in altitude, plus or minus two degrees (2^{o}) in heading, and maintaining a stable hover over a one foot (1') diameter circle on a calm day. Again, the heading and altitude assumptions were made after conversations with Pacific RPV in which the stability characteristics of similar aircraft were discussed. The spatial error assumption of plus or minus six inches (6") in x, y was necessary as a design constraint for the object retrieval mechanism. An obvious conclusion of this assumption was that construction of a retriever capable of being transported by the aircraft and searching the entire six foot (6') diameter 'source' bin was impractical. Regardless, these parameters were assumed until flight testing could either confirm or deny their validity. The assumption's impact on subsystem design was that a retriever must be capable of acquiring disks within the imaginary geometry presented by the aircraft's spatial and stabilization errors.

(3) The vehicle would fly forward, backward, and sideward during the flight. As helicopters fly equally well in any direction at low airspeeds, additional control to accomplish 'hover turns' about the vehicle's z-axis seemed unnecessary. The impact was that subsystems must be designed to function regardless of vehicle orientation within the court.

(4) Separate computers would be required for the guidance/flight control and control of the mission equipment package. Emphasis was made that, if multiple computers were developed, particular attention must be given weight and volume constraints. Additionally, from a maintainability viewpoint, use of common microprocessors might reduce spares, necessary expertise, and possibly cost.

(5) At least one team would be capable of accomplishing the AUVS task. As the team's objective was to win, this required development of a system which would accomplish all requirements provided by the competition rules.

Miscellaneous Taskers. As all system weights to this point were extracted from marketing data, and the aircraft was now available, the aerial vehicle group was asked to prepare a more detailed weight statement.

An analysis of the flight path which would result in as few control inputs as possible resulting in the shortest flight duration was requested.

All groups were asked to provide test, simulation, and evaluation schedules to the system engineer for the Winter and Spring quarters. As a note, this was not possible, due primarily to the design's infancy and team inexperience.

An evaluation of how strong WREK (Georgia Tech radio) emissions were in the competition arena's vicinity was requested of the team's electrical engineering contingent.

Conclusion. Apart from task-specific meetings with the various equipment lenders and supporters, this EXCOM was one of the more historically significant meetings from the standpoint of influencing the ultimate system's design.

Computer Vision System Development.

The vision working group, introduced at the January 4th EXCOM, met to discuss requirements and establish objectives first on January 10th. Goals of the system during this initial phase included:

(1) to locate the strobe lights inside each bin

(2) to find the disks in the 'source' bin

(3) to provide vehicle position feedback

The Dickerson camera with pinhole lens provided a plus or minus 15^{o} field of view. It was hoped that a combination of vehicle position and appropriate optics would allow the system a complete view of the 'source' bin without having to move the aircraft or

slew the camera to find all six disks arrayed randomly in the bin. A specific goal of the group was to recover a disk position to within .5 inches when the target was located less than eighteen inches (18") from the center of the image and viewed from an altitude of sixty inches (60").

A strobe or camera flash, mounted on the aircraft, was shown to be required, based on preliminary camera testing of similarly-colored objects in the laboratory against a black backdrop.

The group anticipated using a single processor with multiple heads to perform the dual navigation/target detection functions.

The disks, when strobed, would be recognized as 'blobs' by the Low Level Vision System (LLVS) onboard the aircraft. A High Level Vision System (HLVS), located at the ground station, would compare the blob locations to current world knowledge and decide which blob was the target. This step was deemed necessary since more than one disk could be present in the image for the first five iterations up and down the court. The HLVS would then output a vector indicating heading and distance to target, relative to the position of the vehicle when the image was taken.

Pacific RPV Visit.

Mr. John Smith arrived at Georgia Tech on January 11th specifically to answer team questions about the Bruiser and to assist the aerial vehicle group in learning required maintenance actions.

During his visit, the team confirmed stability assumptions made about the airframe as realistic, particularly so if the SAS employed on the aircraft.

The Futaba FP-9VHP transmitter used to command the Bruiser possessed nine channels on which aircraft and aircraft system control could be accomplished. It was anticipated that at least seven, possibly eight, of these channels would eventually be

required by the airframe. Therefore, an additional radio was needed to ensure adequate channels were available to control onboard payload. As Pacific had provided the team's Competitor without radio, purchase of additional R/C transmitter was directed. Because simultaneous use of both radios was anticipated, at least 5 Mhz spacing between transmission frequencies would be required in order to eliminate interference problems.

Additional comments made during Pacific's visit included:

(1) Payloads of from five to six pounds in the forward compartment were necessary on previous aircraft to obtain adequate balance.

(2) Electric fish reels capable of winching up to twenty pounds were recommended for use to the object retrieval mechanism designers.

(3) Transmitters should be tested adjacent the chain link fence for interference difficulties. Additionally, it was recommended the team check with local R/C clubs to determine where particular frequency problems existed.

(4) Flights should be accomplished from a paved surface. Inexperience with the aircraft necessitated use of traditional R/C model training gear [Figure 23]. This gear, while able to slide easily on pavement, preventing roll-overs, could catch on grassy surfaces, resulting in mishaps.

(5) A ground run of at least one minute was directed in order to warm up the Bruiser's engine.

Bruiser First Flight.

After failed attempts to get airborne on the previous day, the GT Bruiser flew for the first time on January 23rd [Figure 23]. This flight, ultimately one of the most successful, demonstrated the aircraft's ability to hover stably. Assumptions of altitude and attitude variance appeared validated.

Figure 23 - First Flight of the Georgia Tech Bruiser

Executive Committee Meets (January 25th).

Comments from the System Engineer. For the first time since beginning the project, an electrical engineering student was identified to lead the development of the system's object retrieval mechanism and to oversee vision system development.

Groups within the team had discussed the possibility of 'training' the system to accomplish several of the more basic tasks autonomously and then using these as 'building blocks' toward eventual accomplishment of the entire mission. With significant development of the flight control system yet to be accomplished, however, it was felt that integration efforts, not originally planned until the Spring quarter, should be delayed.

Competitors Announced by the AUVS. A list of competitors from around the United States and a team from Great Britain was announced by the AUVS on January 23rd

[Figure 24]. Various universities on the list had become known to the Tech team through personal and industrial contacts. From this original announcement through the competition, however, little knowledge was available about any competing design scheme, hindering any type of traditional 'benchmark' effort.

Further rules clarifications included moving the vehicle starting area from one corner of the volleyball court to another in order to allow teams access via an existing door. Secondly, teams would not be allowed to set up their systems prior to heats, further restricting any procedures developed for subsystem and component initialization.

No part of the system, in particular antennas and cameras, would be allowed to extrude through the chain link of the fence. Existing physical barriers around the arena were to be considered imaginary planes which could be not penetrated physically by system hardware.

Bins would probably be manufactured of some opaque plastic material and disks would be tossed into the 'source' bin by hand [Figure 1]. Disks landing on their sides would be pushed flat and no disk would be within one disk diameter of the bin edge. In regards to the six foot bins, the Tech team eventually requested permission from the AUVS to construct the bins. It was felt that access to as much competition day 'hardware' as possible would assist the testing and validation effort. Once testing was completed, the team planned to sell the devices to the AUVS for the competition.

Aerial Vehicle Engineer Emphasis. A detailed test plan was developed by the aerial vehicle group. Early emphasis was, in accordance with the SEMP, to further evaluate the Bruiser's technical characteristics. In particular, analysis of available thrust would further clarify design limits to be imposed on payload.

List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California Teledyne Ryan Aeronautical, San Diego, California
California Institute of Technology, Pasadena, California Hughes Aircraft, Malibu, California
Edinburgh University, Forrest Hill, Edinburgh, United Kingdom
Georgia Institute of Technology, Atlanta, Georgia Pacific RPV, Inc., Start-Up, Washington Guided Systems Technologies, Atlanta Georgia
Massachusetts Institute of Technology, Cambridge, Massachusetts ISX Corporation, Thousand Oaks, California
Mississippi State University, Raspet Flight Lab, MSU, Mississippi
University of Alabama, Huntsville, Alabama High Density Control Company, Huntsville, Alabama
University of Dayton, Dayton, Ohio Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas UTA Chapters of AIAA and IEEE
Washington State University, Pullman Washington Hunt Technologies, Inc., Brainerd, Minnesota

Figure 24 - Initial List of Competitors

Early steps to develop the flight control system involved establishing a database of vehicle geometric, aerodynamic, and weight characteristics for use with stability and control simulation tools.

Acoustic and vibration level tests were further planned to identify the environment in which the system's sensors and payload components must operate.

Flight Control System Development. Pacific RPV proposed developing a modified version of the existing SAS for use with the autonomous Bruiser. Development time was to be donated by Pacific, with hardware components to be acquired by the Georgia Tech team. A site visit by Mr. John Moore of Pacific was planned in early February to further discuss the project.

The system would input actual vehicle attitude, altitude, and heading, and output desired readings through an RS-458 bus to all five control actuators. It would consist of two payload 'boxes': the sensors and signal conditioners in one box, and the processor in another. Pacific further proposed a desired sensor suite. An altitude sensor, then being developed by a student group, was to be interfaced with the onboard system.

The navigation vision system would provide global vehicle position to an outer control loop, which would then generate a position offset vector and translate the command to required vehicle attitudes. An initial control system block diagram was drafted and is depicted in Figure 25.

The control system engineer further recommended that vehicle altitude and heading be maintained constant in order to simplify control loop development. In response to this recommendation, vehicle orientation was chosen to be maintained constant along the longitudinal axis of the volleyball court with aircraft nose (positive vehicle x-axis) to the target bin. A constant altitude, to be determined by camera field of view primarily, but secondarily by thrust characteristics obtained in flight testing, would be flown.

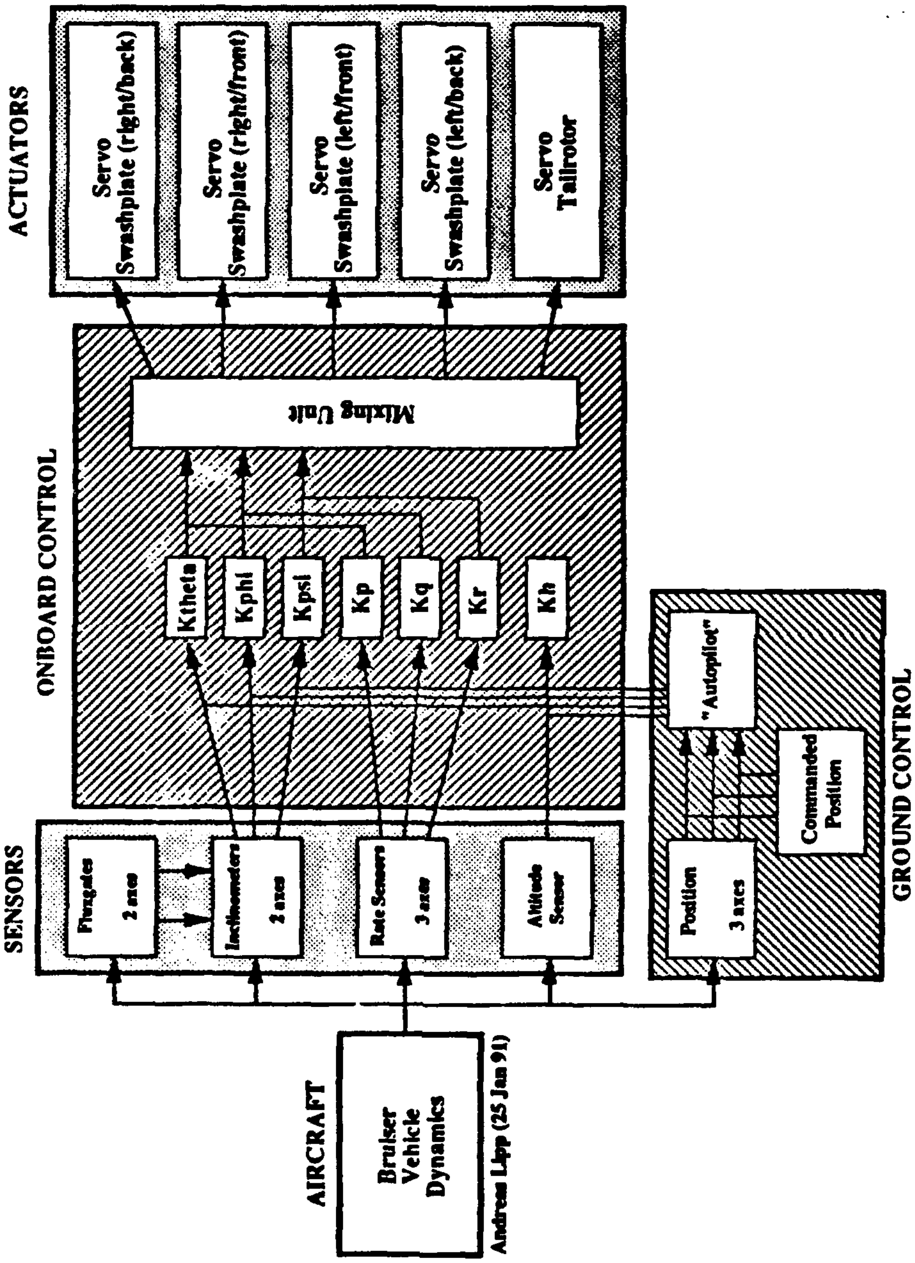


Figure 25 - Preliminary Flight Control System

In addition to design specifications for the object retrieval mechanism already outlined, this constant altitude decision required retraction and deployment by the retriever from hovering flight.

Market Evaluation of Data Link Options and World Model Development.

System Communication. Contact with a several communication hardware vendors was initiated in order to find between the aircraft and ground station (the Futaba radio transmitter would be used as the uplink). Of primary importance, however, was identification of data package sizes and required transmission speeds. Until these issues were further defined, evaluation of competing hardware systems was essentially a 'shot in the dark'.

Likewise, understanding communication required between the system's hardware components, and the format of this communication, was essential to developing code able to receive, store, and further manipulate system-developed knowledge. While unknown at this point, some database of information constituting a 'world model' would be necessary in providing information gathered at some early portion of the flight profile for use later in the mission's execution. As a minimum, it was envisioned the vision system, in its target detection role, would 'find' all six target disks on the first trip to the 'source' bin and remember their location for use as x and y destinations on subsequent shuttles back and forth.

Team Communication.

In addition to struggling with system communication requirements, the data link group attempted to establish an electronic project log on which team members could provide subsystem updates and review progress by other groups. Primarily due to student unfamiliarity with electronic mail procedures, this log was seldom used and eventually abandoned.

Block 2 Schedule Objectives.

An updated schedule was provided to the team on February 8th. The broad design goal of system definition through product engineering resulting in a preliminary design benchmark, as outlined in the SEMP, was still on schedule.

Key subsystem objectives were:

(1) Aerial Vehicle Group. Complete the database necessary to implement ARMCOP. In addition, solid modeling using I-DEAS software needed to commence in order to address unfolding payload weight and placement issues.

(2) Mission Equipment Package Group. Preliminary design of the object retrieval mechanism was to be completed and presented to the team for comment on March 12th, the final Block 2 meeting.

(3) Data Link Group. Wiring diagrams of the Futaba transmitters were to be obtained in order to design digital to analog boards and address other ground station interface issues. In addition, results of the ongoing market survey of feasible downlink components was to be presented for discussion at the February 22nd EXCOM meeting.

(4) Vision Working Group. Evaluation of the Dickerson camera in order to select appropriate external navigation cues was to be completed by February 22nd. Additionally, a second camera purchase decision was to be made after risk evaluation by students in the concurrent engineering course.

Ultimately, system integration was planned to be completed by June 4th, with optimization of appropriate hardware and algorithms to be accomplished during the remaining seven weeks.

Flight Control Development Continues.

U.S. Army Aerostructures Group Joins the Team. On February 1st, formal approval was given Captain Greg Walker of the Aerostructures Directorate at Langley, Virginia to participate as a member of the Georgia Tech team. Captain Walker's primary objective in joining the group was to use lessons learned in development of the Georgia Tech system for the prototype aircraft being developed for the FFRRV project at Langley. A visit was planned to coincide with Mr. John Moore's being in Atlanta to discuss the aerial robot's flight control functions the weekend of February 8-10.

SAS Designer Visit. In pre-visit correspondence, Mr. Moore expressed reservations concerning use of an acoustic system to sense vehicle altitude citing the Bruiser's noise environment. Sound pressure levels while operating over a grassy surface had been measured at greater than 75 dbA at three meters. Mr. Moore's experience with marine acoustic positioning systems proved high noise levels difficult to correct for. In fact, measurements taken during early flight tests over a concrete surface showed vehicle noise levels of 98 dbA at between five and ten feet.

During Pacific's February 8-10 visit to Georgia Tech, development strategies for the outer control loop, with particular emphasis to navigation sensor interface, were debated. An alternative to the proposed onboard vision system presented by both Moore and Captain Walker involved positioning at least three cameras on the ground to track the vehicle's position vice a single camera on the aircraft tracking multiple external cues. Ultimately, the procurement cost of a third camera (two were already being discussed) and calibration times necessary to implement this procedure (only three set-up minutes were allowed) resulted in abandonment of this option.

Additional information gained during Moore's visit included:

(1) The control system would require operational frequencies of at least ten cycles per second (Hz) in order to compensate for natural frequencies of 6 Hz and 10 Hz in vehicle roll and pitch, respectively.

(2) It was possible to take advantage of the vehicle's ground effect limit to assist in controlling altitude.

(3) Selection and incorporation of Watson sensors in the system made development risks extremely low. In particular, use of the Watson Attitude Heading Reference System (AHRS-C300A) [16] would allow Mr. Moore the ability to develop any stability augmentation system to near maturity using equivalent hardware available to him in Washington-state.

(4) Batteries necessary to operate the SAS were described to the mission equipment package group (responsible for power generation). It was recommended that a planning capacity of twice the mission duration in battery power be designed into any direct current (DC) supply.

(5) In addition to the one minute engine warm up, sensors would require at least thirty seconds to warm up and an additional time to initialize prior to flight.

(6) Development of the SAS required Intel development tools. It was expected that, becaust Georgia Tech was an educational institution, these could be acquired at no cost and provided through the team to Mr. Moore.

(7) Mr. Moore would be out of the country in early June. Therefore, significant efforts were planned in order to progress the SAS, if not fully develop it, as far as possible prior to his departure.

The Ultrasonic Altimeter. Design of the acoustic altimeter continued during project work in the School of Electrical Engineering by two team members. The strategy was to provide a 0-5 volt output signal proportional to the Bruiser's altitude. This signal would

constitute the altitude error signal input to the inner loop controller and operate at an update rate of from 10 to 20 Hz.

Helicopter airframe vibrations and noise levels were measured during flight testing. As mentioned, these would influence function of the altimeter.

Polaroid Environmental Grade Ultrasonic Ranging Units and a 6300 Ranging Board were selected as the component hardware. Like components were eventually loaned to the team by GTRI.

A prototype system was to be completed by the end of Block 2 with flight testing scheduled from March 11-15.

SAS Follow-Up. Correspondence from Mr. Moore on February 28th detailed that hardware development for the augmentation system was progressing. Eighty-percent of the necessary parts were already on hand, and code would soon be written. It seemed likely, based on this report, that a SAS might be deliverable on, or about, June 1st.

Bruiser Mishap.

A series of engine tuning problems plagued early flight test efforts throughout the month of February. On February 26th, the Bruiser suffered its first mishap when strong winds forced a hard landing [Figure 26]. As only the landing gear suffered any real damage, repair was accomplished relatively quickly. This type of work, while untimely, resulted in significant gains by the aerial vehicle group in maintenance and repair experience.

Detailed Functional Analysis Using Quality Engineering Tools.

Detailed study of competition requirements using quality engineering tools commenced in early January as work in a concurrent engineering course. A project was assigned to develop a Quality Function Deployment (QFD) Planning Matrix. Customer requirements, as defined in the AUVS competition rules, were deployed against an

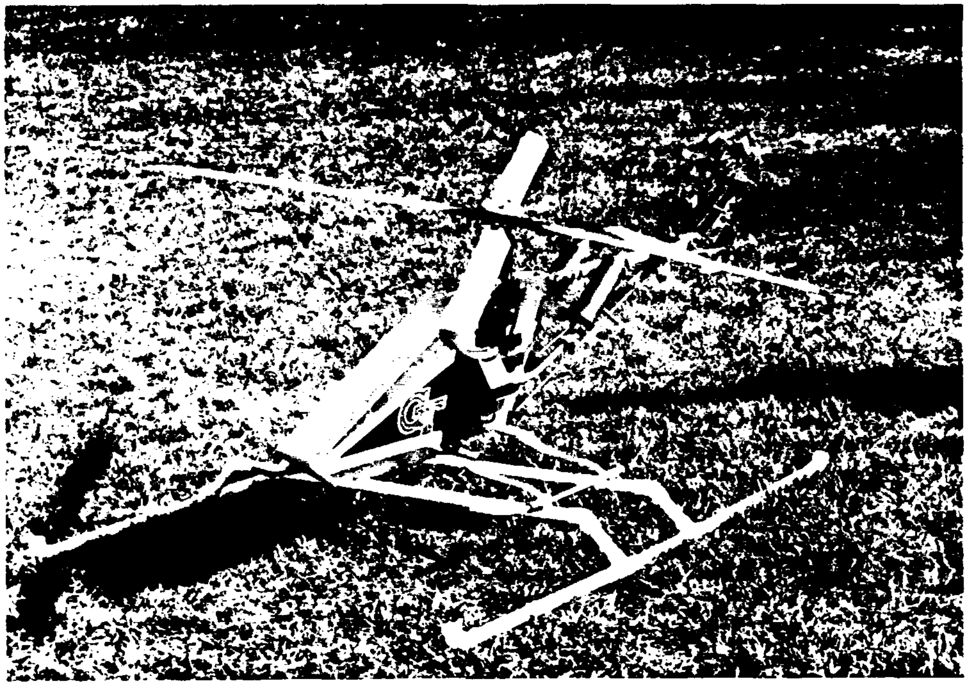
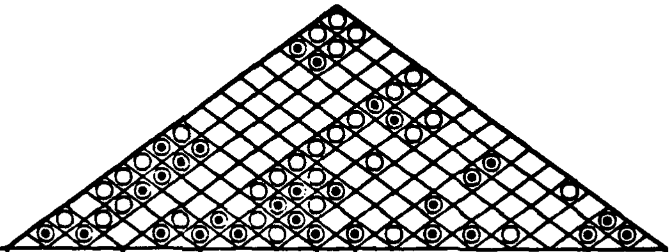


Figure 26 - Initial Bruiser Mishap

essential task breakdown (ETB). Primary-level tasks were taken from top-down evaluation of likely computer code requirements developed by the mission planning and control group in mid-December 1990. Target values for each essential task, using execution time as the objective function, were established. Finally, tasks determined through this analysis to be the most critical, would be further deployed against the work breakdown structure. It was anticipated that identification of hardware components associated with the most critical competition tasks would provide some clue as to how best to apply limited resources in further system development.

Numerical evaluation of the relationship between primary-level customer requirements and second-level essential tasks using a software package called *'QFD Designer'* identified the five most critical essential tasks [Figures 27 and 28]. Neglecting

Autonomous Aerial Robot
QFD Planning Matrix



CUSTOMER REQUIREMENTS \ ESSENTIAL TASKS	IMPORTANCE	System Maintenance: Subsystem Maintenance	Conduct Readiness Checks	Maintain Records	Perform Prelaunch Operations: Deploy the System	Connect System Interfaces	Initialize the System: Initialize Subsystems	Download Mission Data	Start Aerial Vehicle	Launch: Launch	Execute the Mission: Move to Source Bin	Locate Disks	Retrieve Disks	Move to Target Bin	Deposit Disk	Contingency Operations	Perform Recovery Operations: Land	Terminate System
Autonomous Operation	3	○	○	△	○	△	○	△		◎	◎	◎	○	◎	◎	◎	◎	△
Vehicle Requirements	3	○	○		△		△			○	○	○	○	△	△	○	○	△
Contest Time Constraints	2	◎	◎		◎	○	◎		○	○	△	△	○	△		◎		
Contest Restrictions	2	△	△				○				△		○	△	○	◎		○
Course Specifications	2	△	△		△	△	△	△		○	△	△	△	○	△		△	△
Environmental Considerations	2	◎	◎	△			△		△	○	○	○	○	○	△	○	○	△
Disk Specifications	1											△	◎		△	△		
SYSTEM RISK		L	L	L	L	L	M	L	H	H	M	M	H	M	L	H	M	L
TARGETS (seconds)					315	145	150	20	60	7	7	10	5	8.5	1		25	20
ABSOLUTE IMPORTANCE		28	28	5	17	9	23	5	6	27	25	24	29	24	21	32	21	14
RANKED IMPORTANCE		3	3	13	9	11	7	13	12	4	5	6	2	6	8	1	8	10

ROOF	MATRIX	WEIGHTS	ARROWS
Strong Pos ◎	Strong ◉	3	Maximize ↑
Positive ○	Medium ○	2	Minimize ↓
Negative ×	Weak △	1	Nominal ○
Strong Neg ⁂			

Figure 27 - Quality Function Deployment (QFD) Planning Matrix

Top Five Essential Tasks	
1	Contingency Operations
2	**Retrieve Disks**
3	System Maintenance
	Conduct Readiness Checks
4	**Launch**
5	**Move to Source Bin**

Figure 28 - Top Five Second-Level Essential Tasks

the maintenance tasks and contingency operations (not to be considered until the system worked under best case conditions anyway), disk retrieval and system launch proved the most important tasks to achieving customer satisfaction. Rounding out the top five is moving to the source bin. It should be noted that the interaction ratings given each relationship between customer requirements and competition task were subjective. The ratings presented in Figure 27 reflect a cumulative assessment of five teams working on these QFD tables in supporting academic work.

It was possible to determine which hardware components were most applicable to the top five by deploying tasks against the WBS [Figure 29]. The shaded areas of this matrix simply show where system maintenance and readiness evaluations must be applied. This interaction revealed the vision system to have greatest responsibility for the five most important tasks. Of secondary importance was development of the system command software which would provide hierarchical instructions to the system's various components. Therefore, emphasis in further hardware analysis should concentrate on the resources, and risk involved, to develop these components of the system.

Hardware Responsibility Level

P - Primary
S - Secondary
T - Tertiary

Level 3 Work Breakdown Structure Components		Contingency Operations	Retrieve Disks	System Maintenance	Conduct Readiness Checks	Launch	Move to Source Bin
Aerial Vehicle	AIRFRAME					P	
	PROPULSION					P	T
	GUIDANCE	T					P
	FLIGHT CONTROL	T	T			S	
	POWER GENERATION & DISTRIBUTION						
	ANCILLARY EQUIPMENT						
MEP	VISION SYSTEM	T	S			S	P
	OBJECT RETRIEVAL MECHANISM		P				
	POWER GENERATION & DISTRIBUTION						
Mission Planning & Control Station	COMPUTER WORKSTATION						
	SYSTEM COMMAND SOFTWARE	P				T	S
	POWER GENERATION & DISTRIBUTION						
	STATION SHELTER						
Data Link	AIRBORNE DATA TERMINAL	S				T	S
	GROUND DATA TERMINAL	S				T	S
	COMMUNICATIONS SOFTWARE	S				T	S
	WORLD MODEL DATABASE	S				T	S

(Column group heading: Essential Tasks)

Figure 29 - Essential Task Deployment against
Level 3 Work Breakdown Structure Components

Although the Dickerson vision system had been applied in landmark tracking applications, its use on a moving platform tracking stationary landmarks was new. Therefore, the decision was made to purchase a second camera and double development efforts in order to counteract some of the risk involved with this novel application. Additionally, as it comprised one of the more important sensors within the system, its loss or malfunction would be a serious impact. A second system would offset these effects.

Second, as the camera's code would require significant development efforts, and existing code would only function on certain type desktop computer systems, the team decided to purchase a 386SX computer system. It was further assumed that, once camera development was complete, the computer could be used to supplement the Microvax II in the mission planning and control station. In fact, the 386SX eventually replaced the Microvax as the key hardware component within that subsystem.

Further conclusions from the QFD evaluation were additional design constraints on the object retrieval mechanism. Target time values established for tasks to be performed during actual execution of the mission showed that only five (5) seconds could be afforded the retriever to pick up a disk once located. This value was determined after an analysis of aircraft velocity necessary to translate back and forth between the bins and time necessary to acquire and deposit the target disks. Flight velocities from three (3) to six (6) knots were assumed with deposit of the sixth disk 'scheduled' at the 180th second (the three minute limit). Flight tests over a 28' distance (bin center to center) using the smaller-scale training aircraft, revealed that airspeeds of greater than approximately 4.5 knots resulted in the aircraft attempting to accelerate through effective translational lift (ETL). Therefore, slower velocities in transit would be necessary, further restricting retrieval time.

Given that the retriever was to be mounted to the airframe and the aircraft was to hover at a constant altitude (approximately sixty (60) inches), this meant the retriever had to drop, acquire, and retract within the 5 second time.

Mitre Corporation Visit.

On February 21st, Dr. Marc Slack from the Mitre Corporation visited Georgia Tech to be briefed on the project. As his group at Mitre was primarily interested in artificial intelligence applications, Phase II work using the aircraft as a technology test b was determined more suitable for their involvement. However, Dr. Slack agreed to review the team's efforts periodically as another objective viewpoint.

His comments during the team's briefing highlighted the need to conduct early testing with the acoustic altimeter. Experience at Mitre with these type sensors revealed different sonar characteristics from different surface materials. Therefore, evaluation on the competition's black plastic surface should be conducted as soon as practical.

Additionally, he agreed with the team's early January assumption that at least one team would be capable of performing the competition mission. In fact, Dr. Slack characterized Tech's proposed flight profile as the most likely and commented that any improvement over this 'baseline' would be warranted if time permitted.

Concurrent Engineering Project 2.

Continued work on application of quality engineering tools to the aerial robot's development required identification of key Technical Performance Measures (TPM) for the hardware and software components highlighted as most critical to customer satisfaction [Figure 29]. These measures represent the characteristic description, in performance specifications, of a given component. Almost as a byproduct of this study, and for the first time, a relatively clear picture of the entire system was formed. This system block diagram

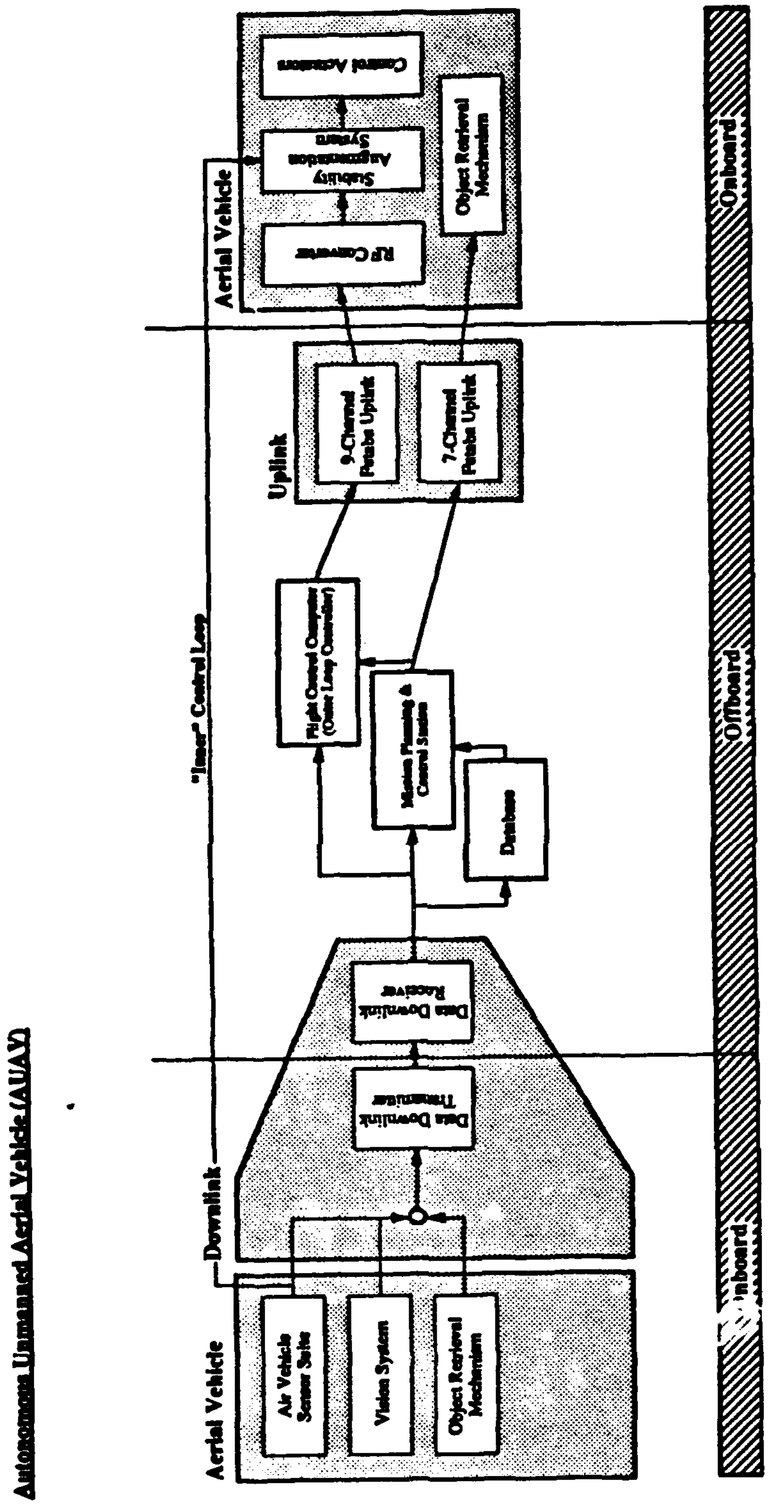


Figure 30 - Preliminary System Block Diagram

[Figure 30] become one of the cornerstone system definition tools and, with minor changes, resulted in near complete system identification by the end of Block 2.

Block 2 Conclusions.

A final Winter quarter meeting was conducted on March 15th. Key issues to be discussed at this gathering were preliminary design of the object retrieval mechanism and results of the data link group's downlink market evaluations.

Object Retrieval Mechanism (ORM) Design. The ORM was to encompass development of a retraction system, retriever, and associated computer codes for the function of each.

A GM8714 Pittman gear motor, connected to a load shaft containing an aluminum spindle, constituted the retraction system's hardware. The load shaft was to be mounted underneath the aircraft using multiple support bearings. The retriever was held in its retracted position through incorporation of an electromechanical brake. An optical shaft encoder was used to let the retriever know its altitude about the ground. A Motorola MC68HC11 microcontroller was used to vary input voltage controlling motor torque output, process data collected by the shaft encoder, energize/de-energize the motor and brake, and to time components thereby assuring smooth operation.

The retriever was to incorporate nineteen (19) electromagnets geometrically positioned so that any disk present underneath the one foot diameter array would be touched by at least one magnet. Disks were to be detected by measuring the inductance of the magnetic circuit, which is affected by permeability of the material in contact with the magnet. Higher voltage readings were produced when magnets touched the metallic target disks. Another MC68HC11 housed the disk location algorithm and generated a 100 Hz square wave in order to perturb the detection circuits and evaluate the inductance readings.

Combining retriever and detector in one hardware component resulted in weight and cost savings. Further algorithm and layout optimization was to be completed concurrent with system manufacture.

Data Link Market Survey Results. With intra-aircraft, and aircraft to ground, communications becoming clearer, evaluation of feasible hardware components for use as the system's downlink was simplified. Further identification of the 10 Hz system operating frequency requirement established a 'bottom line' requirement which, when coupled with proposed communications packet sizes, dictated subsystem selection. Unlike some other hardware components, which were selected for acquisition cost reasons, packet size and operating frequency could not be sacrificed through purchase of a slower, possibly less expensive system.

Figure 31 presents a plot of required baud rate versus package size in order to achieve the 10 Hz cycle time specification. Package size is reflected in bytes and represents the size of the information packet being transmitted from the aircraft to the ground. The 'effective' line of the chart assumes the computer uses fifty percent of its available time for functions other than communication. Therefore, in order to achieve appropriate system frequencies, an effective baud rate of twice the original must be obtained.

As information package sizes to be downlinked were now on the order of 45 to 50 bytes, effective rates of at least 9600 baud were required. Three of five surveyed systems met this requirement. However, only testing would reveal effective rates. Additionally, detailed design would likely result in an increase in packet size. Therefore, 'overdesign' of the downlink components became an objective. In fact, packet sizes approached 80 bytes near competition day.

Knowledge About the Design.

System Definition. A list of technical data, hardware nomenclature, and flight profile scheme was developed to serve as the system's preliminary design. This was ultimately documented in the previously-mentioned Benchmark 1 report and represented the team's knowledge about the design to this stage.

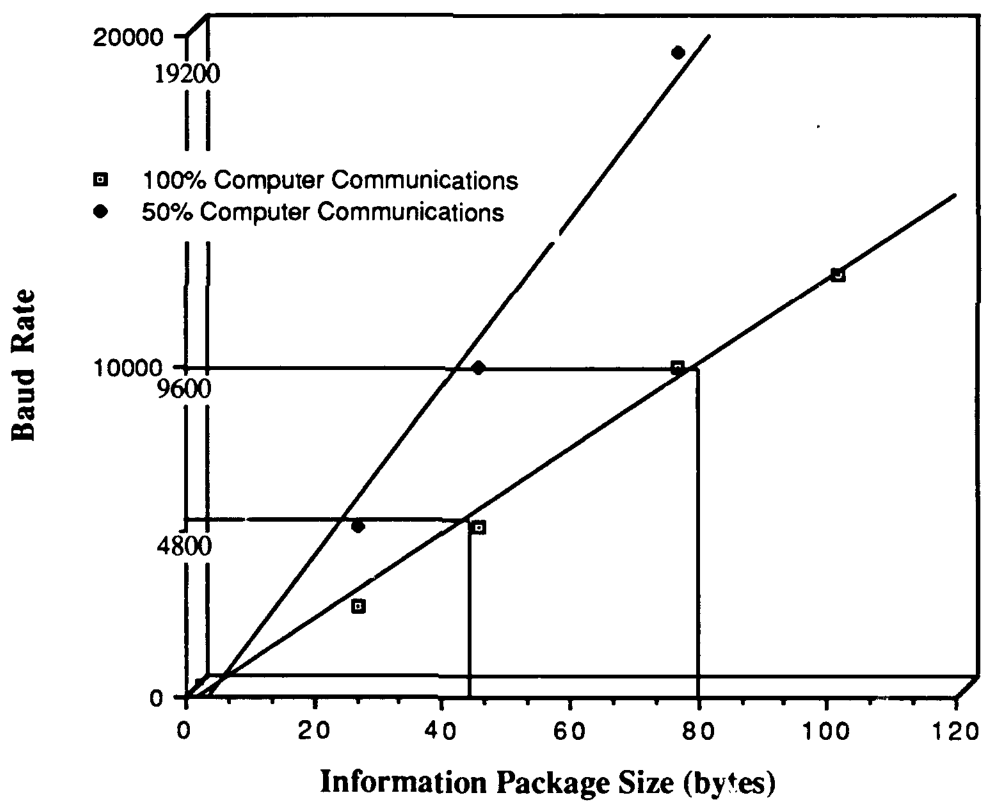


Figure 31 - Information Package Comparison with Required Transmission Speeds (Baud Rate)

Knowledge About the Design Curve. Chapter 1 presented discussion of the 'Paradox of Sequential Design' and qualitatively highlighted how application of concurrent engineering techniques might affect this situation.

During the development of a system, it would be impossible to assess the knowledge about the ultimate design which is known at any point in the development process. For example, what percentage of the final system design was represented by Benchmark 1? However, evaluation of the design process in retrospect, a unique opportunity offered by this competition, allows assessment of cumulative knowledge about the design at any point in the design cycle.

The definition of a Work Breakdown Structure (WBS) was presented in Block 1's discussion. Recall a WBS included hardware pieces, computer code, services and other data which "completely defines the problem". Therefore, it could be assumed that complete knowledge of the work breakdown structure's components would constitute complete knowledge about the design.

Level 4 of the system ultimately developed is presented in Figure 32 in chronological order, based on when knowledge of that WBS piece was gained. Each level four WBS component is considered an equal percentage of the total design's 'knowledge'. For purposes of this paper, the team was considered having knowledge about a component when either a project report describing some subsystem was published, an algorithm describing subsystem computer code was derived, or hardware was received. Knowledge about the design, in this context, did not imply resolution of integration issues or changes made from an original version in component or hardware optimization.

At the conclusion of Block 2 (Winter quarter), approximately 32.7% of the ultimately-developed system was known [Figure 33]. A more detailed discussion of this curve, in qualitative terms, is deferred to the discussion of results.

LEGEND

AV - Aerial Vehicle
MPCS - Mission Planning & Control Station
MEP - Mission Equipment Package
DL - Data Link
ILS - Integrated Logistics Subsystem

	Level 2	Level 4	Date	
	AV	Control Actuators	7-Jan-91	
	DL	Data Uplink Receiver (Futaba)	7-Jan-91	
	AV	Drive System	7-Jan-91	
	AV	Engine	7-Jan-91	
	AV	Fuel System	7-Jan-91	
	AV	Fuselage Structure	7-Jan-91	
	AV	Main Rotor	7-Jan-91	
	AV	Tail Rotor	7-Jan-91	
	DL	Uplink Transmitter (Futaba)	7-Jan-91	
	MEP	Flash Components	10-Jan-91	
	MEP	Navigation Camera	10-Jan-91	
	AV	Stability Augmentation System	11-Feb-91	
	AV	Acoustic Altimeter	19-Feb-91	
	AV	Altimeter Algorithm	19-Feb-91	
	MEP	DC Power Source	1-Mar-91	
	MEP	Magnetic Array	22-Mar-91	
Block 2	MEP	Retraction Assembly	22-Mar-91	Block 2
	DL	Data Downlink Receiver	3-Apr-91	
	DL	Data Downlink Transmitter	3-Apr-91	
	MEP	Omni Optical Device	15-Apr-91	
	MEP	Target Detection Camera	15-Apr-91	
	DL	TTL/RS232 Converter	17-Apr-91	
	MEP	Target Detection Optics	21-Apr-91	
	DL	Downlink 'Post Office'	23-Apr-91	
	MEP	Retraction Algorithm	9-May-91	
	MEP	Retractor Microprocessor	9-May-91	
	DL	Uplink Digital/Analog Board	15-May-91	
	AV	Outer-Loop Controller Algorithm	23-May-91	
	MEP	Power Regulator	26-May-91	
	MEP	Power Supply Algorithm	26-May-91	
	MEP	Power Supply Board	29-May-91	
	MEP	Navigation Camera Calibration Algorithm	29-May-91	
	MEP	Target Detection Camera Calibration Algorithm	29-May-91	
	MEP	Navigation Algorithm	29-May-91	
	MEP	Target Detection Algorithm	29-May-91	
	MEP	Magnetic Array Algorithm	6-Jun-91	
	MEP	Magnetic Array Microprocessor	6-Jun-91	
Block 3	MPCS	System Command Software	15-Jun-91	Block 3
	MEP	External Vision Cues	20-Jun-91	
	AV	Payload Platform	20-Jun-91	
	AV	Inner-Loop Controller Algorithm	26-Jun-91	
	MEP	Universal Joint	28-Jun-91	
	MPCS	World Model Database	10-Jul-91	
	AV	Sensor Suite	14-Jul-91	
	AV	Magnetometer Compass	15-Jul-91	
	DL	'Post Office' Algorithm	25-Jul-91	
	AV	Alighting Gear	26-Jul-91	
	DL	Downlink Antennas	28-Jul-91	
	ILS	Manufacturing/Logistics Support	INCOMPLETE	
	MEP	Power Supply Interface	INCOMPLETE	
	MPCS	Ground Station Power Supply Interface	INCOMPLETE	
Block 4	AV	Fairings	INCOMPLETE	Block 4

Figure 32 - Chronological Development of Level 4 Work Breakdown Structure Components

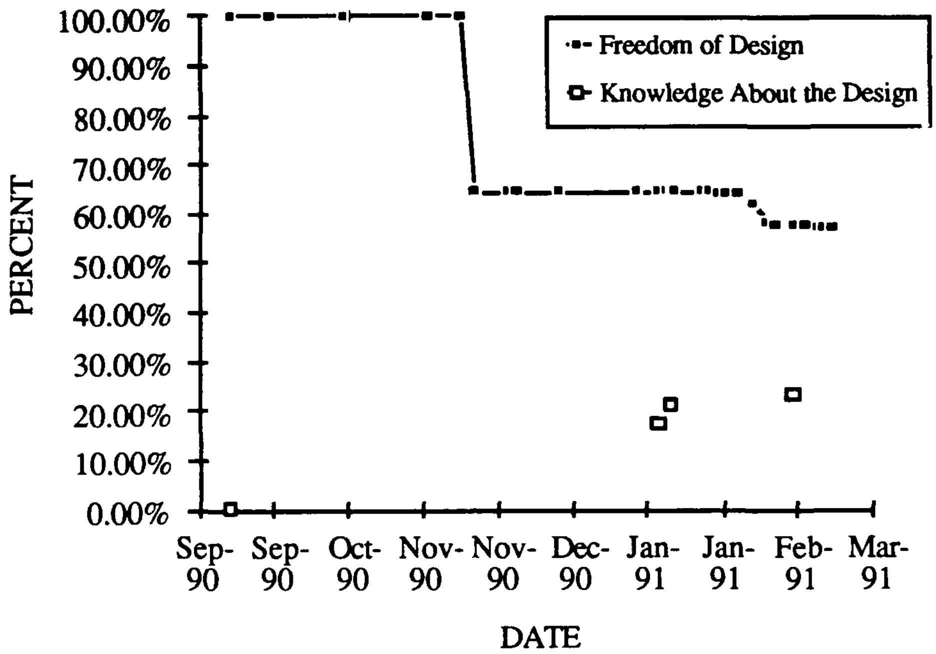


Figure 33 - Freedom of Design vs. Knowledge About the Design of the Georgia Tech Aerial Robot

Assumptions. Assumptions still bearing on the problem are outlined below. Many of the team's original 'guesses' had become knowledge through decision or validation through testing.

(1) Insufficient time was available to build an aerial vehicle.

(2) The aerial vehicle would be capable of holding position to $\pm$ 3 inches altitude, $\pm$ 2^{o} heading, and maintaining stable hover over a 1' diameter circle on a calm day.

(3) At least one team would be capable of accomplishing the AUVS task.

Design Freedom.

As of March 15th, approximately 55.5% of the available design freedom remained to determine the final 67.3% of knowledge about the design [Figure 33].

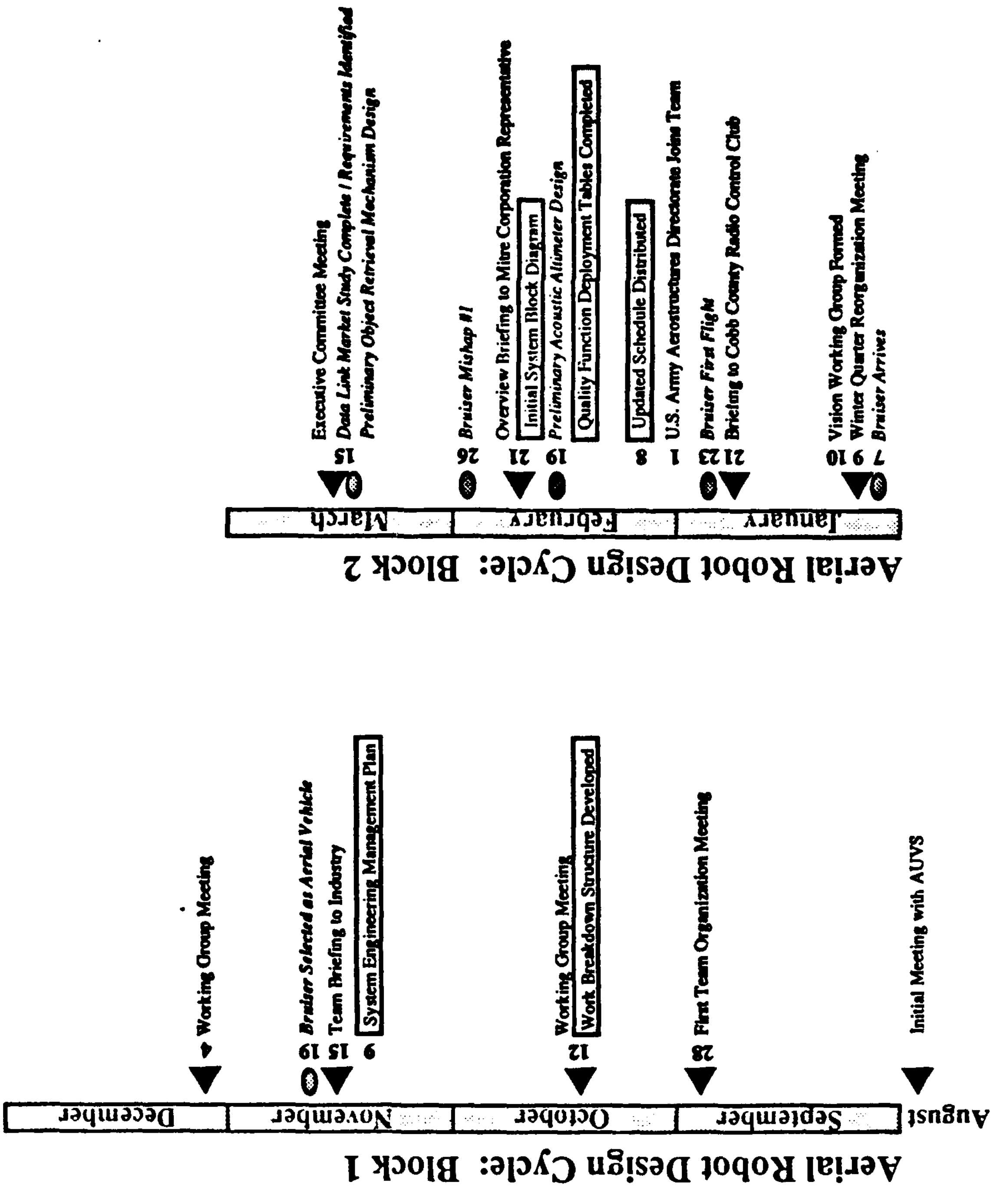


Figure 34 - Key Block 1/Block 2 Design/Organization Events (Cumulative)

Block 3 (April to June 1991) Refining the Design Environment and System Definition

Design Environment Overview.

Time. As classes began on April 1st, the team was left with 34.7% of the system's available development time (119 days).

Student/Faculty Involvement. By this time, the team had begun to stabilize. Many of the students who expressed interest with arrival of the aircraft in January elected not to continue efforts with the team. Design, for the most part, was complete, and difficult hardware manufacture, integration, and computer code development remained. A key consideration since approximately mid-February was students who were to be graduated at the Block 3's conclusion (June commencement). This was to have a tremendous impact on final development of the retrieval mechanism, 'post office', and other peripheral electronic interface issues.

Increased Community Involvement. Near-continuous difficulties with the Bruiser, in particular the drive train and powerplant, resulted in additional R/C modeler participation with the team. Two individuals from a second radio-control club, the Roswell Air Force (RAF), began work with the now experienced aerial vehicle group to identify and solve key vehicle reliability issues.

Mitre Corporation Joins the Team. Partially in response to the information gathering trip by Dr. Slack, and in part due to feedback provided through electronic mail concerning mechanical woes of the aerial vehicle, Mitre provided the team a $600 grant to purchase aircraft spares and repair parts. In return, Mitre was officially added to the team's roster on March 27th. This represented the last funding received by the project during this initial phase.

Facilities. Validation of the navigation camera required developing a scale replica of the competition arena in a laboratory. Necessary space was finally obtained by the team in mid-May.

Competition Update.

A third competition update package from the AUVS revealed that two of the original ten competitors had dropped out [Figure 35].

Hardware Components On Hand	
Aerial Vehicle	Bruiser II
Mission Planning & Control Station	Microvax II
	386SX
Data Link	Futaba 9-Channel
	Futaba 7-Channel
	TRON-Tek ATS 401
Mission Equipment Package	Stinger 70 Integrated Vision System

List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California
Teledyne Ryan Aeronautical, San Diego, California
California Institute of Technology, Pasadena, California
Hughes Aircraft, Malibu, California
Edinburgh University, Forrest Hill, Edinburgh, United Kingdom
Georgia Institute of Technology, Atlanta, Georgia
Pacific RPV, Inc., Start-Up, Washington
Guided Systems Technologies, Atlanta Georgia
Massachusetts Institute of Technology, Cambridge, Massachusetts
ISX Corporation, Thousand Oaks, California
Mississippi State University, Raspet Flight Lab, MSU, Mississippi
University of Alabama, Huntsville, Alabama
High Density Control Company, Huntsville, Alabama
University of Dayton, Dayton, Ohio
Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas
UTA Chapters of AIAA and IEEE
Washington State University, Pullman Washington
Hunt Technologies, Inc., Brainerd, Minnesota

Updated List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California
Teledyne Ryan Aeronautical, San Diego, California
California Institute of Technology, Pasadena, California
Hughes Aircraft, Malibu, California
Edinburgh University, Forrest Hill, Edinburgh, United Kingdom
Georgia Institute of Technology, Atlanta, Georgia
Pacific RPV, Inc., Start-Up, Washington
Guided Systems Technologies, Atlanta Georgia
United States Army Aerostructures Directorate
Massachusetts Institute of Technology, Cambridge, Massachusetts
ISX Corporation, Thousand Oaks, California
University of Alabama, Huntsville, Alabama
High Density Control Company, Huntsville, Alabama
University of Dayton, Dayton, Ohio
Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas
UTA Chapters of AIAA and IEEE

Figure 35 - Updated Competitors List (as of April 4th)

Spring Quarter Reorganization Meeting.

The design team met on April 11th to outline accomplishments to date and strategize effort for the upcoming quarter.

Team Technical Weaknesses. While generally felt the team had grown large enough to accomplish most design objectives, expertise in assembly language programming and someone familiar with digital/microcomputer design was needed. It was agreed specific solicitation would be made using the bulletin board system and that faculty advisors would seek students with these skills.

As previously mentioned, an audio/video transmitter/receiver pair had been received on loan for evaluation and use as the system's data downlink. It had been decided that only data need be transmitted by the vehicle to the ground station and that any necessary visual package would be developed and presented using the downlinked data information.

The difficulty in realizing a combined navigation/target detection camera, and risk in combining these critical functions on a single component, resulted in the decision to employ a second onboard camera. Optics necessary to implement this decision were evaluated, as well as further analysis of necessary external vision cues for use with the navigation device. This decision had significant impact to system spares in that purchase of a second camera had been accomplished in order to counteract the system's risk in testing and evaluation with the device onboard. However, implementation of this design choice, because of the original study, was quick and resulted in minimal impact to system resources.

With most major subsystem components on hand, or in production, purchase of integration-enabling hardware and software was required. Battery power, cabling, commercially-applicable software, and other related items were to be studied. A two-man team was established to further evaluate DC power requirements and sources toward

reduction of an anticipated six (6) pounds of onboard batteries. This six pound figure represented approximately 33% of the available payload.

Computer Function within the System. With anticipated use of both the desktop 386SX and Microvax II in the mission planning and control station (MPCS), and multiple microprocessors onboard the aircraft, the issue of which computer would perform which function needed to be addressed.

While microprocessors were, for the most part, subsystem specific, shared functionality, such as analog to digital conversion, where possible, might eliminate unnecessary redundancy onboard the aircraft. Additionally, this would not require purchase or development of another component, resulting in both financial and weight savings to the system.

On a much larger scale, which hierarchical control functions, graphical displays, and databases were to be stored, manipulated, and run from which computer within the MPCS? Pending algorithm development necessitated resolution of this key issue.

System Spares. While addressed for the aerial vehicle, spares and repair parts for other subsystems had not been considered. Anticipated test flights and unanticipated failures required consideration and purchase of backup components.

Onboard Post Office. Preliminary discussion of an onboard post office was initiated at this meeting. Two onboard vision systems, the stability augmentation system, and object retrieval mechanism were all designed to transmit varying byte packages to the ground control station for either storage or manipulation. How best to collect, sequence, package, and transmit this data needed to be addressed with a fifth microprocessor, or at least theorized to accomplish this function. Additionally, output of all onboard hardware components was in RS-232 format, while the TRON-Tek downlink transmitter/receiver pair operated in TTL.

Integrated Schedule. Sequencing components into some organized integration scheme was now required. Any attempts to develop schedules, however, had proven difficult. Continuing mechanical difficulties with the Bruiser made integration and testing of any component unpredictable. Nevertheless, an integrated schedule was overdue and milestone lists and test schedules were requested from the subsystem engineers.

Aerial Vehicle Status.

On April 14th, one of the volunteer R/C modelers working with the Bruiser on a test stand was injured. While not a design milestone by any means, the event amplified already problem-plagued product testing and resulted in several 'down' days while necessary safety procedures were developed.

The following update was extracted from an April 18th meeting agenda of the aerial vehicle subsystem group:

Payload Placement. Payload layout, to include detailed weight and balance, needed to be refined. In particular, layout decisions resulting in modified payload shelf and landing gear requirements needed to be made so that details could be forwarded to Pacific RPV for their manufacture.

Digital SAS. The updated delivery date was now June 15th although, at one point, March 15th had been projected. The lack of access to Intel development tools, thought to be available to Tech, slowed progress significantly. With funds available, and the continued slip of the digital controller's delivery date, a decision was made to begin development of a backup analog system.

Altimeter. The acoustic altimeter, originally projected complete by March 10th, was still not completely assembled.

ARMCOP Modeling. Stability and control information developed in project work by a helicopter stability and control course, made continued efforts to implement ARMCOP

obsolete. Additionally, ARMCOP was found too conservative for this scale aircraft and further efforts would require significant flight testing which, by this point in time, was impractical.

General Comments. After repeated attempts to obtain necessary product data through flight testing and a myriad of mechanical failures, the aerial vehicle group was only able to react to malfunctions as quickly as possible in an attempt to keep the Bruiser airborne. Any effort to forecast requirements was viewed with a great deal of skepticism.

Vision System Development.

Concurrent development of both computer vision systems was initiated on April 21st, although considerable work with the navigation camera had already been accomplished. The group felt that similar computer codes would be utilized by both cameras and, when compared to the navigation task, solving the target detection challenge was trivial. Therefore, apart from an analysis of optics and related hardware for the target detection camera, primary focus of the vision working group was to maturation of the navigation vision system.

Early vibration testing with the Bruiser mounted on a test stand indicated the camera speed was faster than any rotor frequency. Images taken over time with the camera attached to the nose fairing revealed no shift of the digital data from 'picture to picture'.

Brainstorming resulted in the design of a right circular conic device which allowed the navigation camera a 360° field of view [Figures 36 and 37]. This prevented unwanted camera slewing or using of multiple cameras on the vehicle to view all five external vision cues. The sixth cue, originally oriented along the longitudinal axis of the volleyball court [Figure 38], was deleted due to its obstruction by the rotor mast assembly.

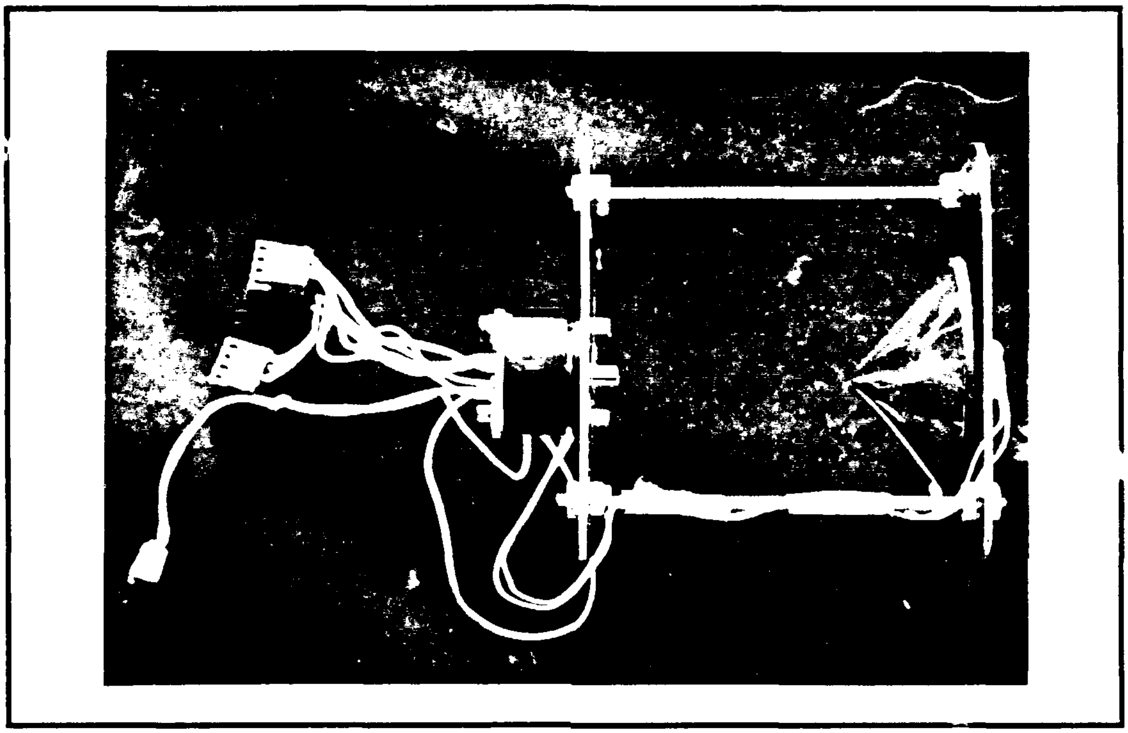


Figure 36 - Navigation Camera Conic Device

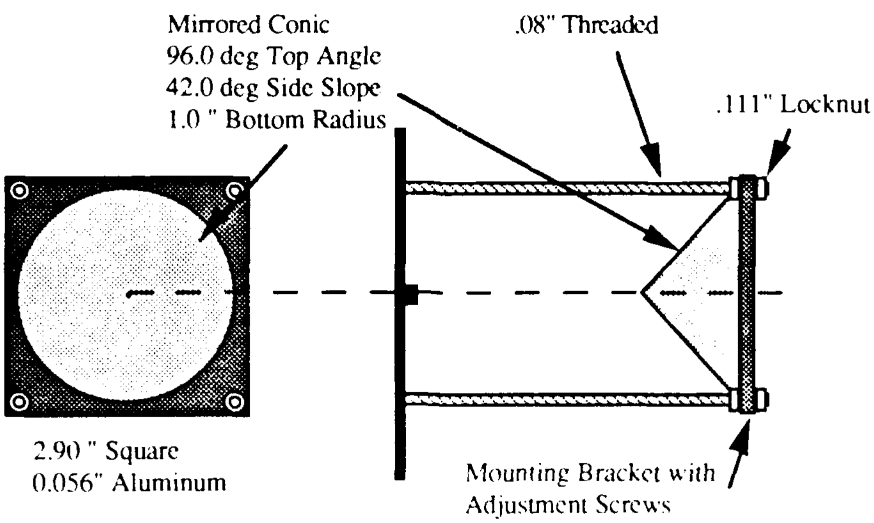


Figure 37 - Navigation Camera Conic Schematic

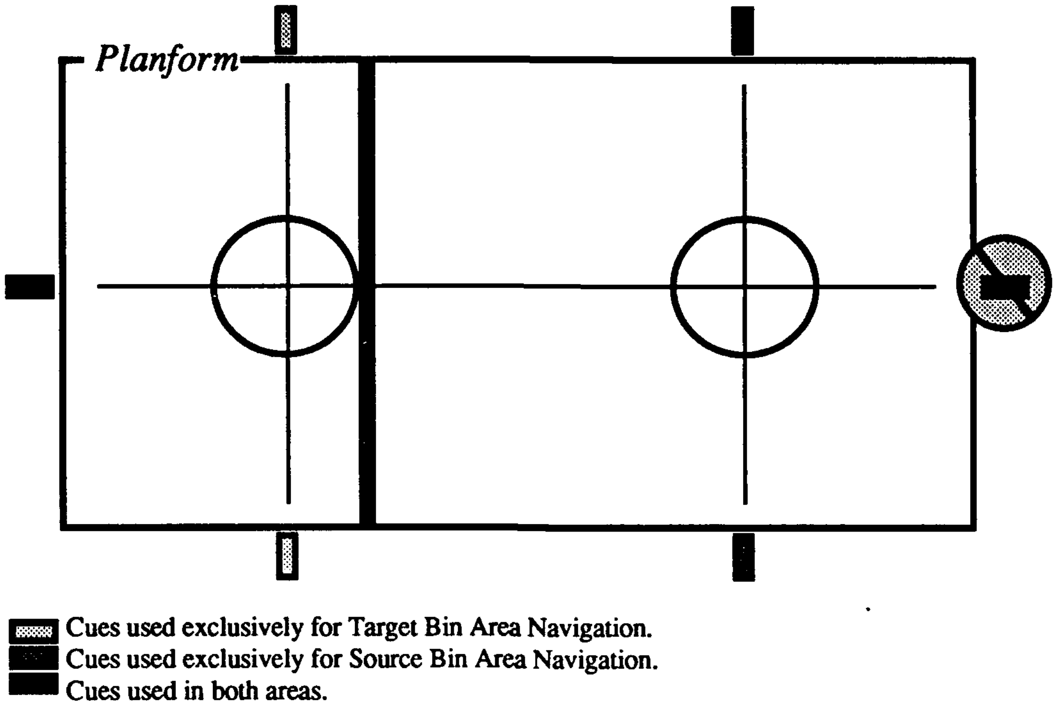


Figure 38 - External Navigation Cue Layout

Data Link Design.

Testing with the TRON-Tek equipment began immediately upon receipt. Field tests for interference revealed significant difficulties in image transmission. Various antenna orientations were attempted in order to isolate the problem. It should be noted the TRON-Tek was not designed for digital data transmission. Therefore, interference in image transmission was perceived to only worsen with attempted digital communication.

Object Retrieval Mechanism Development.

Emphasis of the mission equipment group at this time was primarily retraction assembly manufacture. Coincidentally, testing with the smaller training aircraft carrying a representative payload extended on a string 'tether' revealed significant oscillations of the load underneath the airframe, eventually resulting in loss of aircraft control.

Therefore, modified supports for the lines attaching the array to the retraction assembly were recommended by the aerial vehicle group to the MEP team. In addition, decoupling the retriever from vehicle dynamics was thought feasible through design of an universal joint which would physically mount the retriever to the airframe. Ultimately, a wooden mockup was produced around May 8th. This was further modified, and eventually refined, using computer-aided solid models.

The Onboard 'Post Office'.

A student meeting was conducted on April 23rd in order to resolve functional requirements of the onboard post office. All groups with a component-specific microprocessor were represented at this meeting.

Four microprocessors onboard the aircraft were already advanced beyond preliminary design. Therefore, rather than modify the existing components to interface with the proposed-post office, the post office board was to accommodate current function of the various microprocessors. This device would convert the data from RS-232 to TTL format, receive input at a variety of rates and buffer the speeds to an appropriate sequencing rate between data transmissions, sort the incoming data and discard undesired information, and package and sequence downlinked information packages. The immediate plan was to purchase a piece of hardware which could handle a 40 byte information package.

Additional decisions from this meeting included:

(1) The 386SX would handle all required MPCS functions, less an agreed upon graphics display. This display would be run near real-time and offline from primary MPCS operations. Information to drive the display would be fed through a serial port to the Microvax II (the assumed graphics driver).

(2) Only seven of nine available uplink channels were required for use by the aerial vehicle, even after including SAS and kill switch functions. Therefore, only one

uplink Futaba radio would be used, reducing the system's requirements for a second D/A board, although the second would continue to be developed as a component spare.

An updated system block diagram reflecting these changes is shown as Figure 39.

Interim Schedule.

Although difficult, further efforts to develop an integrated schedule resulted in a weekly task list. Key dates included:

Week of 13 May: Install and test Watson sensor suite on the aircraft.

Week of 20 May: Test onboard power supply and TRON-Tek components in flight.

Week of 27 May: Install/test data link 'post office' on the aircraft.

Week of 3 June: Complete development of the outer control loop in anticipation of Pacific RPV's visit to integrate the SAS.

Week of 10 June: Accomplish onboard navigation testing.

Week of 17 June: Complete onboard navigation testing.

Week of 8 July: Conduct an autonomous flight demonstration.

Week of 15 July: Begin system optimization (note this was originally scheduled to commence the first week in June).

Week of 22 July: Freeze the system.

Competition Update.

The AUVS notified participants the University of Edinburgh had left the event, leaving only seven competitors.

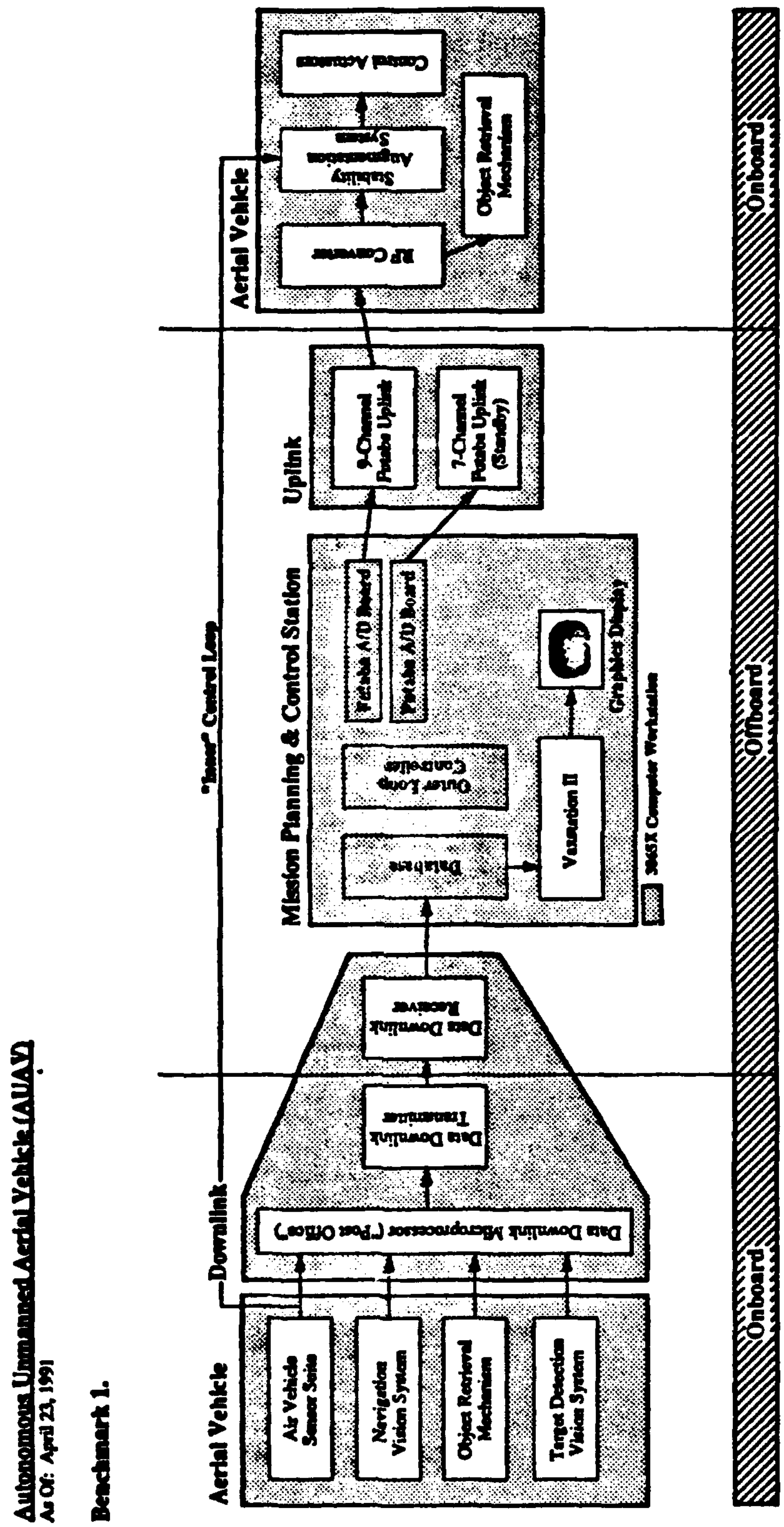


Figure 39 - Revised System Block Diagram

Set Backs.

Bruiser Crash. On May 7th, while conducting test flights, the pilot lost control of the Bruiser, the vehicle caught its right training gear skid tube on the turf, rolled, and crashed. Damage to the Kevlar main rotor blades (destroyed), hub (bent spindle), and servos (gears stripped) was substantial.

Payload Evaluation. Although mentioned as early as mid-March, no significant layout work on the system's payload components had been accomplished. Weights, in particular, were important given Pacific RPV's pending visit to hand off the SAS. Accurate weight estimates would allow simulation tools to calculate loop gains necessary to program the SAS. Obviously, the more exact the weight estimation, the better the gain prediction. Because the solutions to this problem were scattered about the system, and because attempts by the aerial vehicle group to obtain these answers had failed, the system engineer agreed to head this effort.

Object Retrieval Mechanism Components. Many of the parts ordered to manufacture the retraction assembly were on hand, although items requested to be manufactured by the Aerospace Engineering shop were not yet completed. As the aerial robotics effort was not a 'funded' research project, monies to 'buy' shop time were not allocated. Therefore, work accomplished for the team was on a 'space available' basis.

TRON-Tek Interference. Significant interference with the downlink receiver/transmitter pair forced the team back to TRON-Tek for assistance. Antenna matching, power sources, and hardware component failures were discussed as likely problem sources.

Student Graduations. Two of the team's key electrical engineering students would be graduated at the end of Block 3. One engineer was responsible for developing the D/A card used to interface the 386SX with the Futaba transmitter, while the other had done all

preliminary power supply and post office work, as well as provided contributions to the retriever's development.

Onboard Power Supply.

During Block 2, some preliminary analysis of DC power was accomplished by the MEP group. Nickel-Cadmium (NiCd) batteries were ultimately selected because of their high current capability. EAC, a power pack manufacturing company, provided quotes on several different cell packs resulting in the purchase of some components for testing on May 15th. Other pieces, such as a high current voltage regulator and low battery detector, were still being studied for application to the system.

Executive Committee Meeting with Mitre Corporation Partner.

Dr. Slack of Mitre returned to Georgia Tech on May 14th to receive an update on the project, discuss the Benchmark 1 report, and to overview the newly-distributed integrated schedule.

Among the issues tabled at this meeting were:

(1) Make or Buy Plan. While discussed indirectly at earlier meetings, increasing testing and integration requirements would likely make spares and repair parts a significant issue in the coming weeks. An assessment of which components, if failed, could be reproduced within a time which did not result in schedule delays was requested. All hardware exceeding the 'no schedule days lost' guideline, would serve as a preliminary 'buy' list of system spares.

(2) Competition Update. Mr. Michelson of the AUVS attended this update. He informed the team that all transmitters would be confiscated during other team heats in order to preclude unintended interference. Therefore, initialization and information download procedures were to be again be reviewed in order to assess the impact of this

requirement. Further, Michelson agreed to collect information necessary to establish a list of team operating frequencies.

Computer-Aided Design (CAD) Assistance in Magnetic Array Layout.

On May 14th, the MEP subsystem engineer requested assistance in developing a manufacturing template for the magnetic array. CAD-based tools played an important role in the development of this system.

Magnets were spaced within the array such that there was no possibility of 'straddling' a disk. Further, any disk whose center of gravity was within the $\pm$ 6 inch spatial error must be touched by the retriever. Therefore, some optimal geometry of magnets which would both minimize weight and maximize the probability of disk retrieval needed to be obtained. Evaluation using CAD tools resulted in a decrease from eighteen (18) to twelve (12) electromagnets, thereby decreasing payload weight and system cost.

Work from May 15th through June 14th.

It was possible, through default save of electronic mail, to capture some of the more informal correspondence between the system engineer and various team members. This record is likely the most detailed account of team activity and will be addressed as a candidate historical document in the conclusions to this paper.

Spares List. As emphasized in the May 14th Executive Committee Meeting, a 'make or buy list' was needed. Primary attention was to be given those subsystem components onboard the aircraft, as any flight mishap could result in significant damage to the entire system. It should be highlighted here that the integrated schedule took this into account by not scheduling flight testing of all key components simultaneously. As an example, both cameras were not to be tested on the aircraft until final system validation.

Aerial vehicle spares lists were heuristically developed, although detailed analysis of model helicopter failures may have made this evaluation more 'proactive'. A second

engine and hub assembly were purchased from Pacific, as well as spare composite and wooden main rotor blades and a variety of spare parts.

The mission planning and control station group identified workstations which could be borrowed at the 'last minute' were some major system malfunction to occur.

Given that the vision system manufacturer was located on campus, most components deemed appropriate for a spares list could be replaced within one day at no cost premium.

Within the data link subsystem, conversations with TRON-Tek revealed their ability to replace a transmitter within two to three days. Two complete post office systems were to be manufactured. Beyond this second component, replacement, as was the case for any printed circuit board, was approximately two weeks and $250.

The only spare component to be stocked for the MEP group was a gear motor and electromagnets. Further testing was to be accomplished in order to evaluate appropriate repair parts options.

Pacific RPV Visit. In light of tremendous reliability and maintainability difficulties with the Bruiser, Mr. Smith of Pacific RPV agreed to an unplanned trip to Georgia Tech to assist the team with the vehicle over the weekend from May 30th through June 3rd. Feedback from this trip indicated the Bruiser had been mechanically optimized for upcoming receipt of the stability augmentation system.

Vision System Development Update. As of May 23rd, the vision group reported the navigation camera still on schedule, with slight delays in code development for the target detection system.

Code manipulation did result in RS-232 camera output as fast as 32.25 Kbaud. Speed increases once thought to require component replacement at a cost of approximately

$100. However, this 1000% speed increase was accomplished through minor software manipulation.

Continued testing with the navigation vision system revealed it to be oversensitive to an initial guess of vehicle position. In order for the camera to function correctly, vehicle yaw attitude would be required as an input to the camera microprocessor. This input requirement resulted in modification from a 'one-' to 'two-way' communication port between the post office and the navigation camera.

Outer Control Loop Algorithm. Estimates on May 23rd put coding the outer loop control algorithm at least two weeks behind schedule due, primarily, to coordination difficulties between the code's developer and programmer.

Power Supply. As of May 25th, no battery packs had arrived, although the first order had been placed a week earlier. In addition, further delays occurred while the team searched for an alternative circuit board manufacturing source. This, in retrospect, was unnecessary in light of the system's positive budget status.

Object Retrieval Mechanism. Printed circuit boards (PCB) for the retriever arrived during the week of May 20th and were being loaded with components. The retriever still required additional shop work and these hardware delays forced a postponement in lift evaluation of the gear motor on hand. Shop components were finally received and handed off to the MEP group on May 28th. Recall that analysis of mission timelines only allowed 5 seconds for disk retrieval. In addition, as the retriever must be completely up prior to aircraft displacement, retraction as quickly as possible was required. Subsequent testing was expected to finalize the spindle and motor arrangement within the week.

Post Office. Circuit board design for the post office had not left the team for the manufacturer's as of May 25th. Final transmission speeds of the four microprocessors interfacing with the post office were required, in addition to finalized byte formats.

Acoustic Altimeter. The altimeter was completed on May 27th, roughly two months after originally projected.

TRON-Tek Interference Difficulties. Conversations with TRON-Tek concerning the team's continuing interference difficulties resulted in further study of antenna matching and receiver/transmitter orientation. On May 30th, the data link group was put in contact with a subcontractor used by TRON-Tek for various antenna design tasks. Nose dimensions, shelf sizes, component layout, and receiver/transmitter position within the system's set up was provided this organization in order that a more detailed analysis could be completed.

Spring Quarter Wrap Up Meeting.

A team In Progress Review (IPR) was conducted on June 7th. Data format for transmission to the onboard post office was reviewed. Package size had now increased to 56 bytes, primarily due to the camera's inability to handle the more cumbersome position calculations. This validated selection of the TRON-Tek hardware over a marginally effective 9600 baud modem. A review of subsystem status' showed all components from one (1) to three (3) weeks behind schedule.

Use of the Microvax II was abandoned. Maintenance contracts, valid from June to June, were now due for renewal while the 386SX had demonstrated itself capable of handling all necessary MPCS functions. Further expenditure of monies to support the Microvax seemed unwarranted. It was still anticipated that a graphics 'driver' would be required.

Updated SAS Delivery Estimate. June 9th correspondence from Mr. Moore of Pacific RPV indicated progress on the SAS had slowed considerably. Although he offered an older SAS to the team until delivery of the new component could be accomplished, the

team felt time to enable this new SAS would detract from other outstanding issues. Delivery was now anticipated the weekend of June 22-23.

Only when the Bruiser was shown to be stable and reliable in hovering flight could subsystems and components be integrated for testing, evaluation, and, hopefully, subsystem validation. The team was directed to pursue the alternative analog controller as quickly as possible.

June 10 - 15: A Final Spring Push.

Again, excerpts from electronic mail logs provided an overview of several ongoing activities before the quarter break. Team activity could be characterized as 'non-stop' from this point through July 29th.

Acoustic Altimeter. The algorithm used to determine altitude from the array of three acoustic sensors employed an averaging scheme. Were a sensor to fail, this scheme was not robust enough to compensate. However, circuit design and code being at the stage they were with less than six weeks remaining, a decision was made not to modify the altimeter.

U-Joint Manufacture Supported by Solid Modeling Tools. With preliminary testing completed, an 'airworthy' design of the universal joint was required. Several two-dimensional drawings were recreated on a solid model already in use. Although many dimensions were missing from the 2-D sketches, clearances, piece dimensions, and alignment considerations were readily obtained through manipulation of this 'soft prototype' [Figure 40]. These measurements, extracted from a combination of the solid model and sketches, were eventually used in the shop during component manufacture [Figure 41].

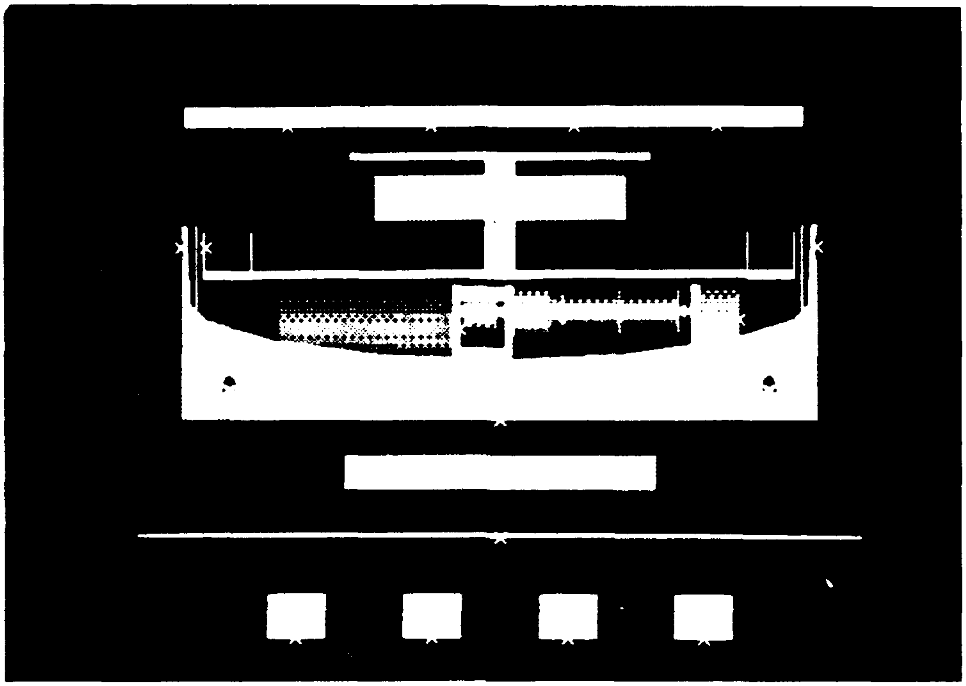


Figure 40 - I-DEAS Solid Model of Retraction Assembly

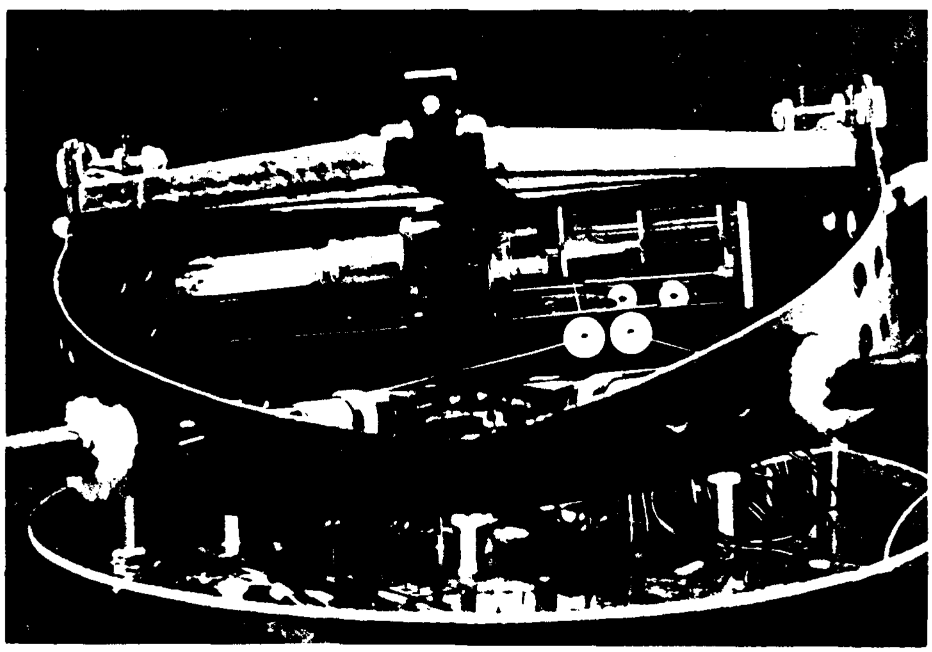


Figure 41 - Completed Retraction Assembly

Knowledge About the Design.

Student engineers had knowledge of slightly greater than 73% of the ultimate design at the conclusion of Block 3 [Figure 42].

Assumptions. None of the assumptions outlined at the conclusion of Block 2 had been resolved: that there existed insufficient time to build an aerial vehicle; that the vehicle would be capable of holding position to $\pm$ 6 inches in x, y position, $\pm$ 3 inches in altitude, and $\pm$ 2^o in heading, and that at least one competitor would be able to perform the specified mission.

It was hoped that aggressive flight testing would establish realistic design parameters, in the form of actual vehicle spatial errors, for the navigation system. However, reliability and maintainability difficulties precluded any significant flight activity. Tests with the navigation camera on a tripod in a gymnasium with lights arrayed at representative distances did reveal that two-dimensional spatial accuracy on the order of inches was possible.

Design Freedom.

Roughly 15.3% design freedom remained to accomplish 27% of the design [Figure 42].

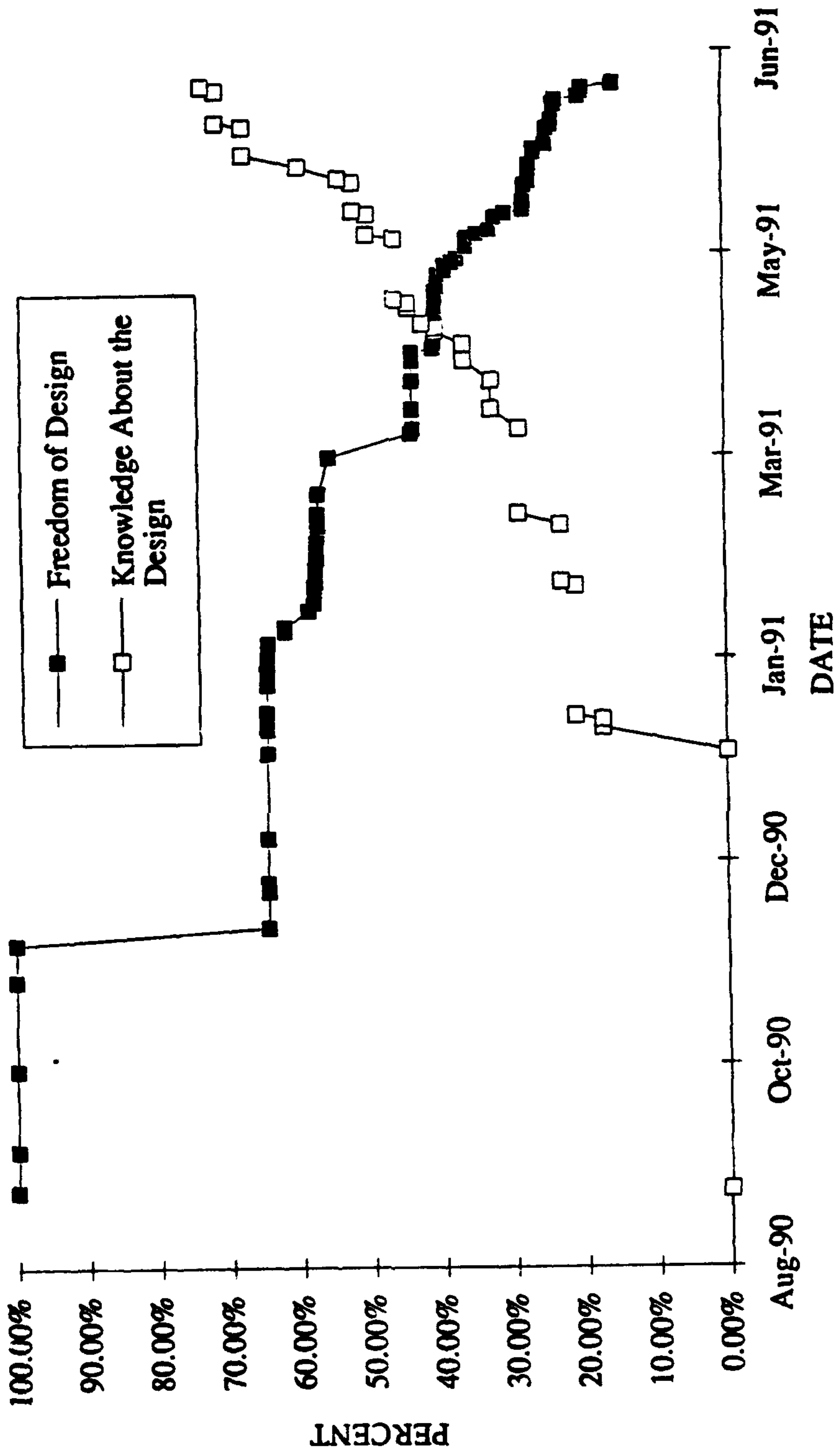


Figure 42 - Updated Freedom of Design vs. Knowledge About the Design of the Georgia Tech Aerial Robot

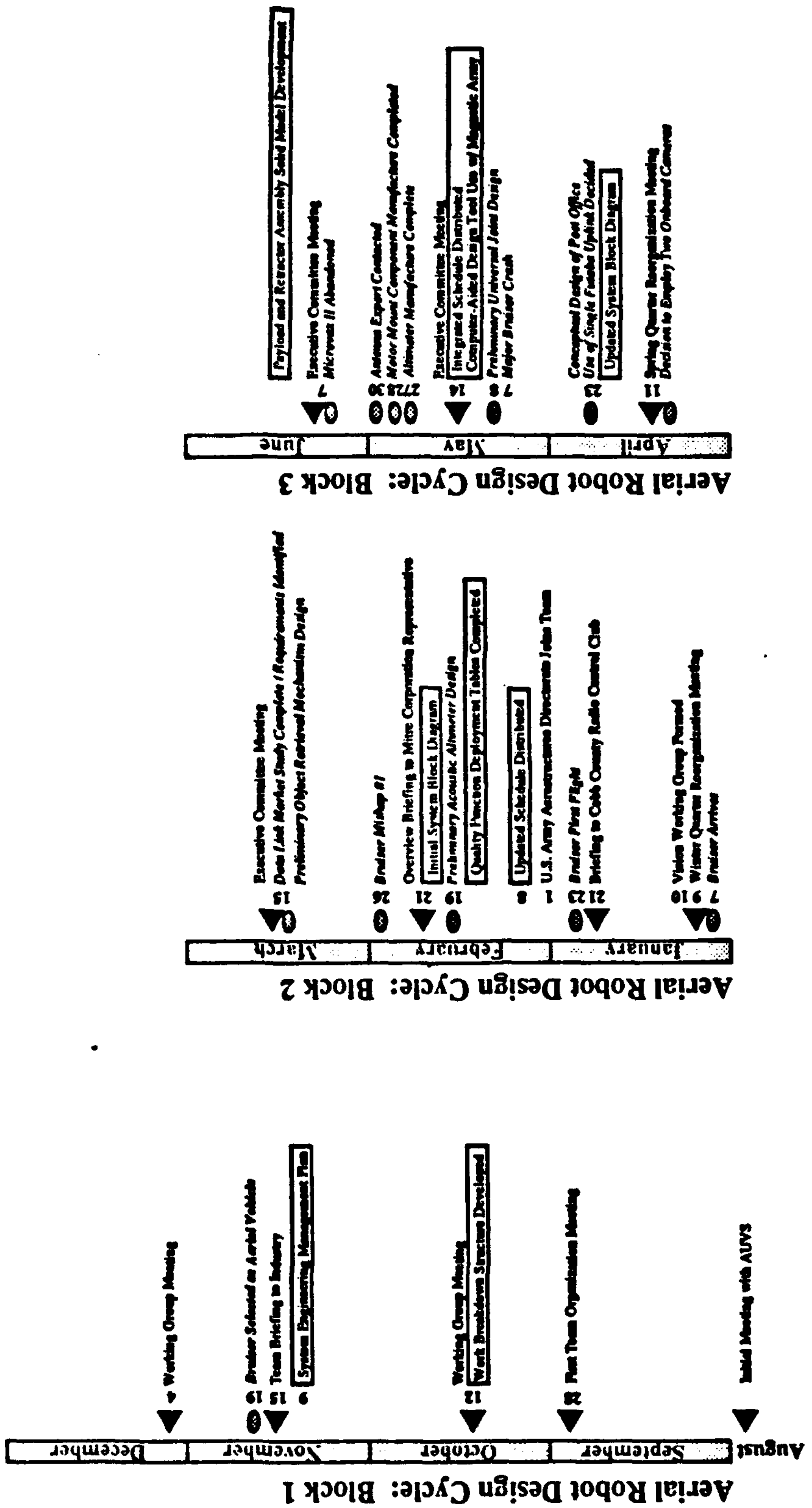


Figure 43 - Cumulative Design/Organization Events through Block 3

Block 4 (June to July 1991)
Integration and Chaotic Conclusion

Design Environment Overview.

Time. 9.9% of the available design cycle was left to the team on June 25th.

Manpower. Although three key team members had been graduated, the team had been relatively constant since the end of Block 2. Given the team's roster, however, only eight or nine of seventeen members listed were involved in making significant effort toward design objectives.

Budget. While it became necessary to oversee spending for a period of time during conclusion of the state's fiscal year, the team enjoyed sufficient funds to complete the effort.

Competition Update.

As teams made lodging and travel arrangements for the competition, it became apparent that only five of the remaining seven teams would actually attempt the mission on July 29th: the Massachusetts Institute of Technology, the University of Dayton, California Polytechnic State University, the University of Texas at Arlington, and Georgia Tech [Figure 44].

Stability Augmentation System Integration.

A final trip by Mr. John Moore of Pacific RPV to Atlanta was planned over the period June 25th through July 1st to integrate the stability augmentation system. It was hoped that by establishing a stable vehicle through SAS employment, integrating the onboard power supply, and mounting the forward payload shelf, that a vehicle ready to accept subsystems as rapidly as could be integrated would be provided.

Captain Walker would also arrive at Tech to observe integration issues which might be applicable to his FFRRV project.

List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California
Teledyne Ryan Aeronautical, San Diego, California
California Institute of Technology, Pasadena, California
Hughes Aircraft, Malibu, California
Edinburgh University, Forrest Hill, Edinburgh, United Kingdom
Georgia Institute of Technology, Atlanta, Georgia
Pacific RPV, Inc., Start-Up, Washington
Guided Systems Technologies, Atlanta Georgia
Massachusetts Institute of Technology, Cambridge, Massachusetts
ISX Corporation, Thousand Oaks, California
Mississippi State University, Raspet Flight Lab, MSU, Mississippi
University of Alabama, Huntsville, Alabama
High Density Control Company, Huntsville, Alabama
University of Dayton, Dayton, Ohio
Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas
UTA Chapters of AIAA and IEEE
Washington State University, Pullman Washington
Hunt Technologies, Inc., Brainerd, Minnesota

Updated List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California
Teledyne Ryan Aeronautical, San Diego, California
California Institute of Technology, Pasadena, California
Hughes Aircraft, Malibu, California
Edinburgh University, Forrest Hill, Edinburgh, United Kingdom
Georgia Institute of Technology, Atlanta, Georgia
Pacific RPV, Inc., Start-Up, Washington
Guided Systems Technologies, Atlanta Georgia
United States Army Aerostructures Directorate
Massachusetts Institute of Technology, Cambridge, Massachusetts
ISX Corporation, Thousand Oaks, California
University of Alabama, Huntsville, Alabama
High Density Control Company, Huntsville, Alabama
University of Dayton, Dayton, Ohio
Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas
UTA Chapters of AIAA and IEEE

Final List of Competitors for the First International Aerial Robotics Competition
Cal Poly State University, San Luis Obispo, California
Teledyne Ryan Aeronautical, San Diego, California
Georgia Institute of Technology, Atlanta, Georgia
Pacific RPV, Inc., Start-Up, Washington
Guided Systems Technologies, Atlanta Georgia
United States Army Aerostructures Directorate
Mitre Corporation, Arlington, Virginia
Massachusetts Institute of Technology, Cambridge, Massachusetts
ISX Corporation, Thousand Oaks, California
University of Dayton, Dayton, Ohio
Dayton Chapters of AIAA, ASME, and IEEE
University of Texas at Arlington, Arlington, Texas
UTA Chapters of AIAA and IEEE

Figure 44 - Final Competitor Listing for the First International Aerial Robotics Competition

As a minimum, the power supply was necessary to fully test the SAS onboard the aircraft. A temporary payload shelf had been developed to 'house' the Watson AHRS. Once adjusted for stable flight, the retrieval mechanism was planned to be mounted so that control loop gains might be adjusted to account for greater mission gross weights and different centers of gravity, as well as to compensate for the changing system dynamics during extension and retraction of the magnet array.

After arrival on June 25th, Mr. Moore completed some final coding and began bench testing the SAS on Thursday, June 27th. Three SAS modes were to be coded: (1) an open loop (pilot-in-control), (2) closed loop (autonomous), and (3) a partially open loop (integrators in some channels open and others closed). This latter mode facilitated autonomous takeoff when the system was artificially constrained by the ground.

Development of components all over campus produced a variety of test difficulties. First, radios being used to finalize design of the D/A boards were needed concurrently to test the SAS. Typically, these radios would be used over extended periods of time in tests and returned to the aerial vehicle group with dead power supplies. Second, the power supply had been designed and built to provide sufficient DC power for a three to six minute flight. This battery life was obviously insufficient to support prolonged flight testing. Lastly, the batteries used required twelve hours to recharge.

Ultimately, alternative power supplies were 'constructed' from D-cell batteries. The result was one hour of transmitter power to twenty minutes of SAS power for a required three hour test period.

These coordination problems resulted in a poor testing effort by the team. Mr. Moore's departure on July 1st left the team with a SAS which still required adjustment, a sensor suite with 'dead' roll channel, and a mechanically marginal vehicle.

D/A Board and Kill Switch Development.

Although significant work was already accomplished, by the time the student responsible for this component was graduated, little technical handoff had been afforded the team. Therefore, the team took advantage of Captain Walker's presence in Atlanta during SAS integration and tasked him with completing the boards.

The D/A card was finished and connections from computer-to-Futaba transmitter were manufactured. A 'kill' switch was wired in a fail-safe mode to the safety pilot holding the radio. During an autonomous flight attempt the pilot could take control of the aircraft by simply releasing the switch. Details of this work were outlined to the data link group prior to Captain Walker's departure.

I-DEAS Solid Payload Model.

As already mentioned, packaging was recognized as a crucial issue during Block 2. Significant attention was not, however, given the problem until mid- to late-June. A solid model of all payload components to be mounted on the aircraft was developed. Through use of simple geometric shapes, most components could be accurately modeled.

Each component was detailed and weighed before attempting the model. Once developed as a solid, physical properties could be calculated. As an example, given the volume of a camera circuit board and its mass, density of the component could be numerically obtained and entered into the database for that solid. Recalculation of the solid's physical properties could then yield mass and moments of inertia about any set of axes. Similarly, grouping components into subsystems allowed rapid calculation of vehicle weights and moments.

Spatial relationships were determined using simple point-to-point options available at the terminal. The data obtained was then entered into a standard spreadsheet for

determination of the vehicle's center of gravity. Ultimately, complete modeling of the aircraft and its components would eliminate the spreadsheet's utility.

The forward payload area is shown in Figure 45. Note the comparison of this solid model to the ultimate vehicle layout forward of the firewall in Figure 46. In addition to weight and balance calculations, lengths determined from the solid model were translated to cabling and other physical interface problems.

Antenna Development.

Antennas specific to the team's proposed flight altitude and ground station location were to be developed and delivered the week of July 1st at an estimated cost of less than $500. This previously unexpected cost, and the loss of two electrical engineers, forced the team to abandon efforts at developing the backup analog controller.

Shop Work.

Component manufacture and access to a shop became critical issues during the last four weeks of preparation. It has already been discussed that no funding was available to contract out shop work. Everything requiring shop time and materials was being accomplished on an 'as available' basis. The Aerospace Engineering school, however, agreed to allow the team primary access to the AE shop over a period of three days beginning on July 8th. Efforts were taken to ensure all remaining shop work was addressed within this window. Parts to be manufactured included components for the object retrieval mechanism and aircraft spares.

Bruiser Return to Washington for Repair.

Continuing difficulties with the Bruiser forced the team to send a member with the aircraft back to Pacific RPV over the period 11-15 July. Mechanical problems, as well as SAS adjustments, were not being solved adequately at Georgia Tech.

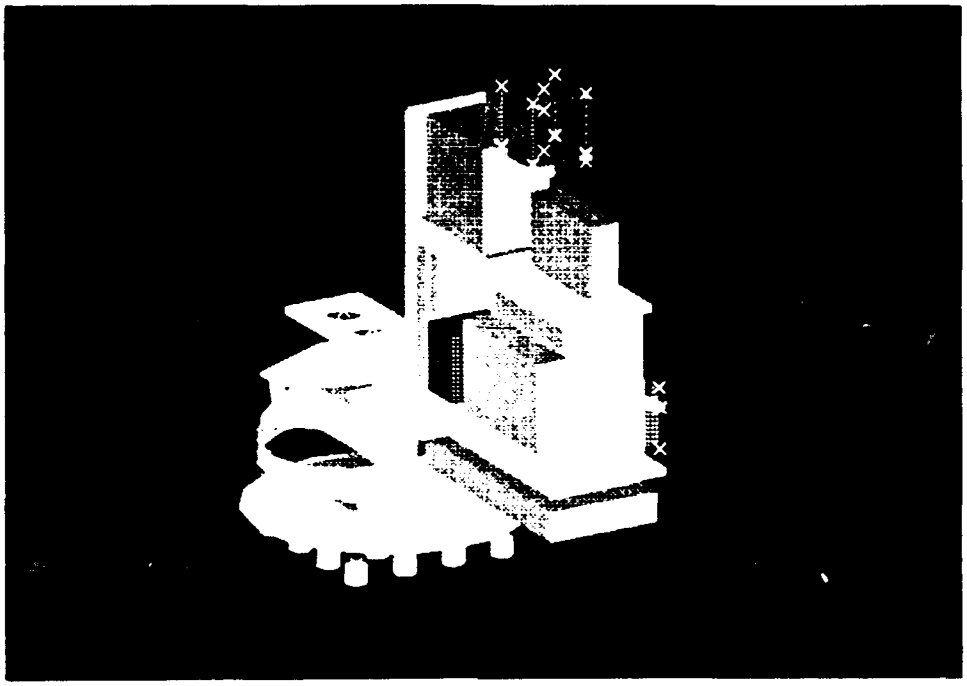


Figure 45 - I-DEAS Solid Model of Forward Payload Area

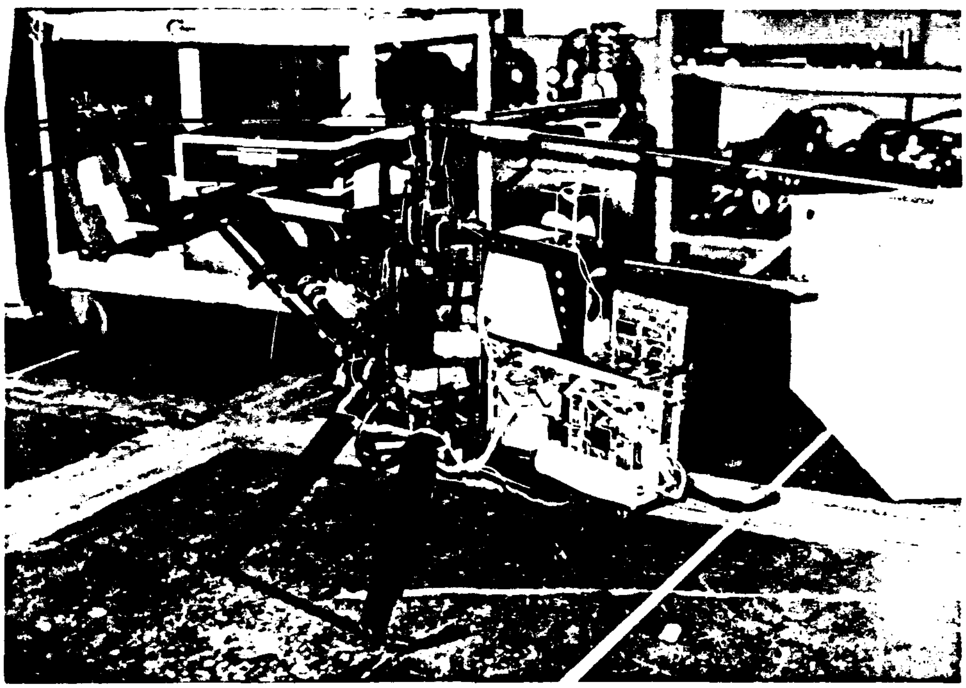


Figure 46 - The Georgia Tech Aerial Robot

Flight testing, while at Pacific, was characterized as successful. On one flight, control sticks on the Futaba transmitter were maintained in a neutral position with hand off the controls. Altitude variation was estimated at approximately 10 meters. Even with this positive progress, a tail-rotor blade separated from the aircraft in flight, continuing mechanical troubles for the aircraft.

One Week to Go.

A myriad of technical details preoccupied the team from early July on. On July 22nd, one week prior to the competition, the systems status was as follows:

Aerial Vehicle. The vehicle was reassembled, less the tail rotor assembly, following its return from Washington. New tail rotor blades had been ordered, but were not yet available. The modified payload shelf was mounted and new landing gear from Pacific RPV, large enough to accommodate the object retrieval mechanism, was enroute. The gear was designed to accommodate lateral and longitudinal rotation of the retrieval mechanism in the universal joint of up to 15° in both axes. Estimated mission gross weight was approximately 36 pounds. Flight testing in Washington had demonstrated lift capabilities slightly over 40 pounds.

Vision Systems. The navigation camera was mounted to the aircraft. Code optimization continued, with particular attention devoted to the navigation camera's sensitivity to sunlight.

Object Retrieval Mechanism. Code for the magnet array microprocessor was still incomplete. Minor mechanical problems still existed in the retractor's ability to lift the array both level and quick.

Post Office. Debug efforts were extremely slow. Minor problems had occupied the few remaining electrical engineers involved with the project for nearly four weeks. As

this component ultimately determined whether or not the system could communicate with the ground station, primary attention was focused to finishing the post office.

D/A Boards. Hardware was near completion. Integration to the 386SX was expected to be rapid, particularly given Captain Walker's return to Atlanta for the competition. On July 23rd, testing verified six of eight D/A channels working perfectly.

TRON-Tek Downlink. The data link group had successfully demonstrated near 90% accuracy with available antennas. The matched antenna set discussed previously had still not been received.

Electronic Mail 'Blackout'.

From Friday July 26th, through Monday the 29th, the system engineer directed all communication between team members be conducted face-to-face or by telephone. Time necessary to send and receive electronic correspondence could not be afforded.

The majority of the team worked non-stop from Saturday morning until the competition commenced.

Significant attention centered around completion of the onboard post office and vehicle flight testing. It was not until early Monday morning, however, that the post office was finally completed.

Flight testing continued to be plagued by reliability problems. On Friday evening, the Bruiser lost a tail-rotor blade for the second time [Figure 47] resulting in damage to the tail-rotor hub and 'vertical fin' assemblies. To the aerial vehicle group's credit, the vehicle was overhauled and ready for further flight testing within several hours.

Testing with the SAS on Sunday evening showed significant improvement in vehicle stability and control. Integration of the acoustic altimeter with the SAS, however, resulted in erratic altitude variation leading to a hard landing [Figure 48]. Finally, at approximately 4:30 am on Monday, July 29th, an engine failure grounded the system.

Figure 47 - Tail Rotor Blade Separation

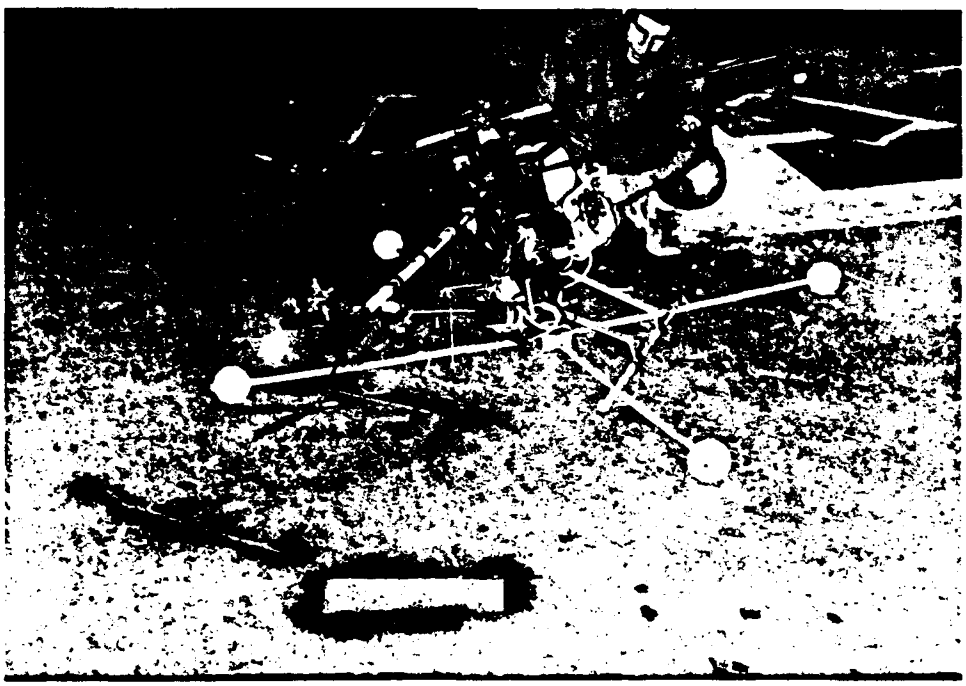


Figure 48 - Bruiser Hard Landing

While sufficient time was available to repair the aircraft, difficulties with the downlink, a nonfunctioning retriever, and assorted integration issues not yet addressed made a safe and successful attempt at the competition's mission profile near impossible. Given the time available, the team was directed to attach all payload components to the aircraft and prepare a static display of other subsystems.

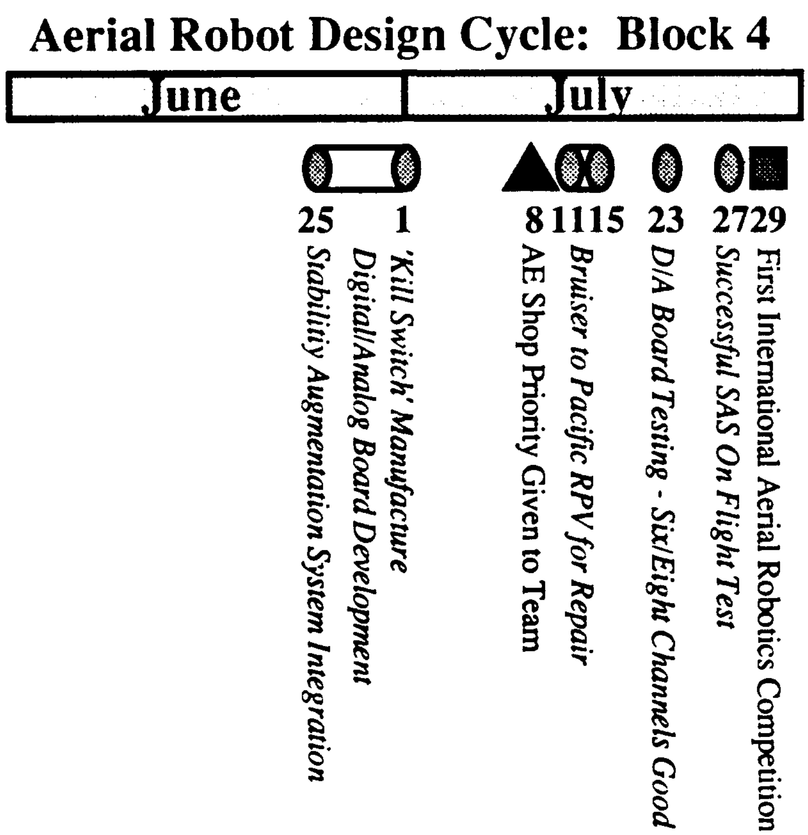


Figure 49 - Significant Block 4 Design/Organization Milestones

CHAPTER IV

RESULTS

The First International Aerial Robotics Competition

Nearly 60 students from five universities arrived at the competition arena the morning of July 29th for the First International Aerial Robotics Competition. Representatives from industry, the Department of Defense, and numerous media organizations supplemented a crowd of interested spectators, team affiliates, and family members. Throughout the weekend, teams had been afforded the opportunity to finally see the wide variety of 'aerial vehicles' which would attempt the AUVS-sponsored competition.

The Massachusetts Institute of Technology.

As expected, the MIT team intended to utilize a .60 series R/C helicopter. In addition, however, the team began construction of a second vehicle after arrival in Atlanta on Friday night. This system, a hovercraft, utilized a garden leaf blower and small 'inner-tube' arrangement. Its retrieval system consisted of a small 'armlike' device which would be thrown into the bin and sweep the area for disks. The MIT helicopter relied heavily on

vision for both navigation and disk retrieval, much like the Georgia Tech entry. Rather than use an onboard vision system for navigation, however, an offboard camera tracked the fluorescent-red-painted forward fairing on the small helicopter. A ground station, operated out of a recreational vehicle, was 'connected' to the vehicle through a high-speed modem.

Ultimately, MIT's target vision system failed, forcing their withdrawal from the competition. The team did attempt to demonstrate their hovercraft [Figure 50] and retriever arm under remote-control with mediocre results.

Figure 50 - Massachusetts Institute of Technology's Hovercraft

The University of Dayton.

Unlike the four other competitors, Dayton's team spent little time in the competition arena over the last few days leading to the event. A series of laser devices were mounted on the arena fence which would ultimately create a set of 'laser planes'. It was interesting to note that the three teams intending to use external cues all placed their devices at virtually the same locations about the fence. Dayton's aircraft, another .60 series helicopter, was mounted on tripod landing gear which suspended the aircraft approximately 3 feet off the ground [Figure 51]. A retriever arm was mounted between the tricycle landing gear. Once airborne, the vehicle would navigate about the arena by 'riding' on the laser planes.

The vehicle was not able to leave the starting area. Two attempts at takeoff resulted in the aircraft tipping back on its landing gear, with the third attempt resulting in the aircraft tipping forward and right, crashing into the arena floor and destroying the main rotor blades.

California Polytechnic State University.

Cal Poly had caused considerable concern through the final two months leading to July 29th. First, their system had been described as being 'low risk' and likely to achieve a good portion of the mission profile. Second, the team had asked permission of the competition sponsor to ship their system nearly a month early, something that never occurred. It had been revealed, however, that the team was composed entirely of undergraduate engineering students, considered by many a liability given the technical scope of the problem.

The system was self-contained, although approximately 200 pounds and just under the 6' cube size restriction imposed by the AUVS. This hovercraft [Figure 52] employed a superstructure on which the tactile disk retrieval system was mounted. As the system was not capable of flying over either the 1' tall ring or 3' tall central barrier, the arm had

Figure 51 - University of Dayton's Aerial Vehicle

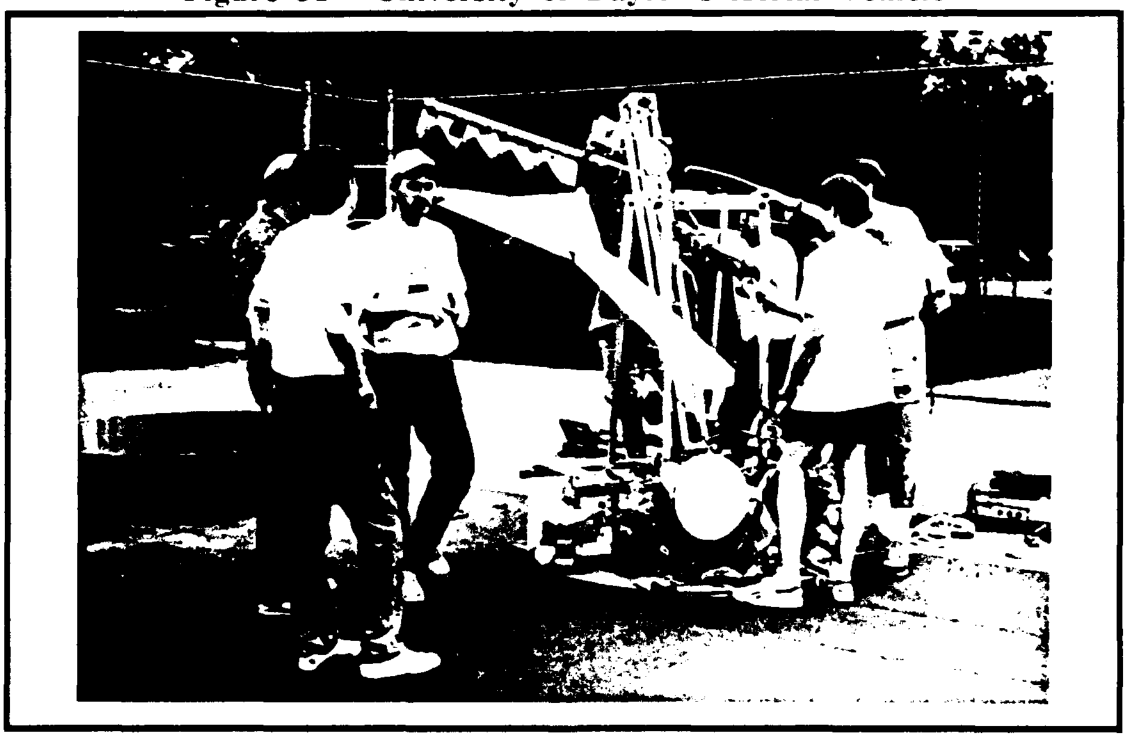


Figure 52 - Cal Poly's Hovercraft

been designed to reach into the ring and sweep the entire bin. A small 'gate' would close on the first disk sensed resulting in all but that disk falling off the retriever when the arm was retracted. Once at the central barrier, the arm would drop the disk into a chute which projected over the wall and aimed at the target bin. Navigation was by 'dead reckoning'. The system was manipulated by hand over the intended 'trajectory'. Computers would then store the path in memory and duplicate the intended route while autonomous.

Although the team eventually put their system in the arena, the vehicle exhibited no computer control. With team assistance, the retriever was demonstrated to work as intended.

The University of Texas at Arlington.

UT Arlington utilized a prop tail sitter as their aerial vehicle [Figure 53]. Structurally modified from another aircraft specifically for this competition, the aircraft weighed slightly less than 20 pounds. Navigation was accomplished by means of a Loran-type system comprised of acoustic sensors arrayed around the competition arena. The onboard computer could triangulate position from the various distances measured by the array of sensors. Disk retrieval was accomplished by means of a target detection camera and single permanent magnet. All necessary computing was accomplished onboard the vehicle.

In its only heat, the vehicle was successfully launched and found the source bin. This flight had been intended to test the navigation system only, thus no target retrieval devices were attached to the airframe. As the vehicle attempted to settle into a hover, the training gear impacted the side of the source bin and threw the vehicle off balance. It impacted the arena floor resulting in damage to the prop and at least one control surface.

Figure 53 - UT Arlington's Aerial Robotics Team and Prop Tail Sitter

Competition Results.

The AUVS agreed the competition had failed to produce a clear winner. Therefore, the $10,000 tuition prize was divided among the five participants commensurate to the level of success achieved in the competition arena. UT Arlington was awarded first place and $3,000, the University of Dayton and California Polytechnic State University each received $2,000, and the Massachusetts Institute of Technology and Georgia Tech each $1,500.

Time between successive aerial robotics competitions had originally been envisioned at from eighteen months to two years. However, as the competitors had demonstrated significant progress toward the competition's requirements, the second event was decided to take place in June of 1992, again at Georgia Tech.

Rules modifications were discussed at a post-competition meeting. Shorter bins (less than 1'), modified bin placement (central to each half of the volleyball court), different central barriers (paper as opposed to wood), and court dimensions were addressed. Many of these recommended rules changes were adopted when the Second International Aerial Robotics Competition was announced in early October.

Figure 54 - Georgia Tech's Team with the Bruiser at the First International Aerial Robotics Competition

CHAPTER V

ANALYSIS OF RESULTS

Was the Customer Satisfied with the Result?

The success or failure of design ultimately rests with the customer's assessment of the product. For the aerial robotics team to have evaluated its success would have been to miss the point of concurrent engineering all together. Recall Taguchi's definition of quality relies on the loss a product causes society. Therefore, the Association for Unmanned Vehicle Systems was asked to evaluate the five competitors. Using customer requirements developed with the Quality Function Deployment Planning Matrix, the teams were rated on how well their entry satisfied the competition's objectives. This matrix is presented in Figure 55. Entries were graded against an 'ideal' aerial robot system as perceived by the competition's sponsor, the AUVS.

Autonomous Operation.

Although none of the entries exhibited a great deal of autonomy in the competition itself, all of the entered systems received at least a 4 out of 5. Cal Poly's aerial robotics system, because it required no ground station or external navigation cues, received the highest score. Georgia Tech and MIT both received the '4' scores because they required

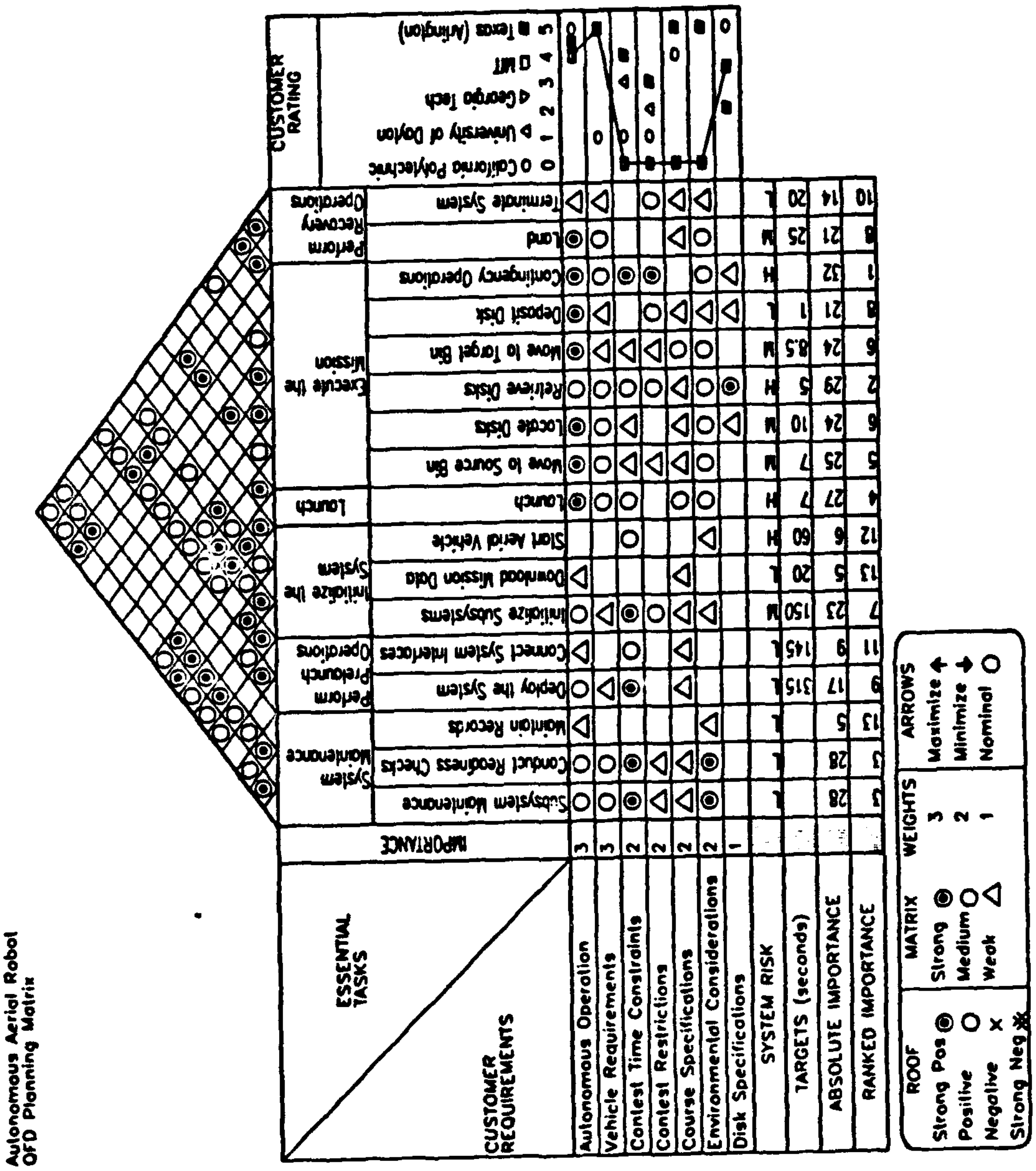


Figure 55 - Quality Function Deployment Planning Matrix with Customer Ratings

both offboard computing and external navigation cues. This indicated a philosophy of autonomous systems on the part of the AUVS which may have been learned through *stronger customer interface* during the conceptual design phase.

Vehicle Requirements.

Specifically, aerial vehicles were perceived to require some type of VTOL capability, at least six minutes of flight endurance, and capable of controlled flight within the geometry of the competition arena.

All of the vehicles except Cal Poly's received a maximum score of 5. This was attributed to technology spin-off potential, while the Cal Poly hovercraft was competition-specific.

Contest Time Constraints.

These constraints were the three minute system set-up time, vehicle start period, and three minute mission performance time.

Note that only those teams who actually attempted the competition received a score. UT Arlington's acoustic cues were perceived to be the quickest to install and their vehicle was reasonably reliable in the start area. Both the University of Dayton and Cal Poly were rated better than MIT and Georgia Tech, although their set up and vehicle preparation times were rated less than desirable by the customer.

The customer allowed considerable deviation in interpretation of the set-up rule, as evidenced by Dayton's positioning of their laser devices more than 24 hours before the competition and MIT's emplacement of a data link component the night before. Feedback from the AUVS highlighted mission execution time limit as the most critical. The lesson learned was that the team's interpretation of the important requirements was incorrect. On this point, the 'Strong Interface with the Customer' tenet of successful concurrent

engineering was certainly violated. In fact, consideration of set up time restrictions ruled out other, possibly more optimal, navigation and communication methods.

Contest Restrictions.

These restrictions included limiting the number of team members inside the court to start the aerial vehicle to two, landing inside the bins only, and picking up disks singly.

Georgia Tech and MIT, again, received a '0' score. However, the customer perceived the system, if demonstrated, would have performed to a '5' score. Cal Poly was penalized for the number of people necessary to operate their system. Both Dayton and UT Arlington scored relatively well, and were perceived capable of a maximum score given their systems had actually flown.

Course Specifications.

These customer requirements dealt with the course dimensions and composition, to include bin placement and the designated start area.

Only those systems which actually left the start area received a score. Cal Poly, although given a '4' score, was not perceived to be capable of remaining within the arena boundaries under autonomous control. Texas again received the highest score, although all of the remaining teams, including Texas, were viewed capable of remaining within the course's dimensions in flight.

Environmental Considerations.

Systems were required to be robust to the environment presented in a competition environment (ie. photo flashes, noise, etc.) and capable of operating in July-type weather for Atlanta.

While only California Polytechnic State University and the University of Texas at Arlington received scores, all systems entered were perceived capable of satisfactory performance in this setting.

Disk Specifications.

All systems entered were judged to have theoretically sound retrieval subsystems. Cal Poly's mechanical arm was determined to possess the greatest probability of successful disk retrieval. The Texas retriever was ranked the worst design due to its vision-assisted disk acquisition and single permanent magnet.

In general, although the designed systems fell short in many categories of satisfying the AUVS mission requirements, the event was judged a success. The "look at reality in the engineering world"[26], was highlighted at having made all the competition's participants winners.

What Went Wrong with the Hardware?

The 'Bruiser' Aerial Vehicle.

The underlying assumption throughout design of this robotics system was that development of an aerial vehicle at Georgia Tech was impractical given the competition's date and short design cycle. Therefore, selection of an 'off-the-shelf' aircraft would allow the team's design resources to be aimed at development of the more critical payload components.

While selection and receipt of the Bruiser represented the first increment of knowledge about the design gained by the team, development of a stable system capable of

26. "1991 Aerial Robotics Competition - Lessons Learned and Ingenuity", Unmanned Systems, Vol. 9, No. 4, Fall 1991, p. 45.

accepting hardware for test and validation was never obtained. *As of the competition date, the aerial vehicle was more than six weeks behind schedule.* Mechanical malfunctions plagued the aircraft during the entire system development cycle. Specific reasons for the Bruiser's poor performance are to be addressed in other studies, however, drive train component reliability was at the forefront.

The team's supposition that subsystem validation and testing could be accomplished on the Bruiser resulted in no alternative airframe being developed as either a competition backup or test aircraft. In addition, the team considered assessment of the aircraft's vibratory and acoustic environment and its impact on payload components critical. No simulation packages could adequately duplicate this regime, and without this analysis, integration would surely prove less than successful.

Evaluation of the aircraft's dynamics could not be accomplished through available simulation tools, due primarily to scaling problems at this small size. Extensive calibration efforts were not possible owing to the short development time available. Even with these tools, significant flight testing was likely required in order to validate their solutions. This type testing, given the high failure rate, was not possible.

In sum, mechanical failure of the airframe ultimately resulted in the team's inability to exhibit anything in the arena on July 29th. *Because the system could not be demonstrated to the customer, '0' ratings were given in four of seven customer requirement categories.*

The 'Home Court Advantage'.

The team was perceived to have a significant advantage, situated virtually adjacent the competition arena. Ambient conditions in the court, electromagnetic spectrum, and other key issues could easily be evaluated. However, none of these studies were accomplished, although discussed at more than one team gathering. Power was not

available in the arena until one week prior to the competition, severely hampering vision system development. Efforts to solve this problem went unrewarded.

Finally, the team spent considerable time discussing the impact of WREK radio tower's location adjacent the court, commenting on the contribution of the chain-link fence to communication difficulties, and highlighting the unusual spectrum created by a national HAM radio convention. Even with this, *no interference testing with the TRON-Tek hardware was conducted in the arena until July 28th.*

Integration Issues.

While many of the system's components did not reach maturity by the competition date, those that did suffered from an incomplete consideration of key hardware integration issues. Electromagnetic interference among payload components, proper grounding, cabling, and a variety of other interface issues continued to surface as late as the morning of July 29th.

What was flawed was the team's perception of integration. As outlined in the design team's SEMP, integration was to be accomplished during the Spring quarter (Block 3). The system engineer failed to realize, however, that *integration is to be designed into the product, and not a consideration at some specific point in the design cycle.* Design For Manufacturability (DFM) and Design For Assembly (DFA) are important considerations at the conceptual design phase. These tools, as highlighted in Chapter 2, are not yet available on a wide scale to the Georgia Tech team.

While the Joint Project Office's documents on UAV development were used as guidelines for this system, *insufficient attention was paid the DoD's emphasis on Joint Integration Interfaces (JII),* or interface specifications. Establishing criteria for the mechanical and electrical interface of one component to another is as key to establishing performance specifications for that single hardware piece.

Finally, in addition to DFM and DFA, *the system must exhibit appropriate Design For Test (DFT) attributes.* Particularly given that all components were to be tested and validated on the competition aircraft, sufficient power supply, as an example, must be available. Regardless, a system-level test scheme must be established to ensure key component development and subsystem integration milestones are met.

What Went Right with the Hardware?

Vision System Development.

While some problems still remain, the navigation vision system, originally perceived a system weakness, was successful in demonstrating the order accuracy necessary for implementation in this mode. The use of this component on a moving system tracking stationary landmarks was a first. Modifications to camera output speed, among other functions, were successfully implemented.

TRON-Tek Application to Digital Data Transfer.

Although designed to transmit audio and video information over short distances, the team was able to provide new application for the TRON-Tek hardware. Successful digital data transfer between two terminals, operating at 19,200 baud, was achieved for over fifteen minutes with 100% accuracy.

Sophistication of Design.

While viewed by some as a team downfall, the system's sophistication resulted in positive evaluations from a variety of sources. Application of the system to other tasks, originally intended in Phase II, has already been initiated in discussions with the Environmental Protection Agency (EPA). As an indicator of the design's versatility, none

of the competition's major rules changes necessitated significant deviation from the team's current design strategy. Clever engineering of the conic device and inductance scheme in disk retrieval, were likely candidates for duplication on other school systems.

What Was Wrong with the Design Environment?

Time.

Establishing the Design Environment. *In academia, establishing the design environment is a key time segment of the system's overall development cycle.*

Industry involved in system or product design are typically organized, financed, equipped, and managed to accomplish that task. Departments with engineers trained in the design process are located in facilities which provide access to design-oriented software packages, computer-aided engineering workstations, and other relevant design tools. Finances adequate to, as a minimum, develop a successful design proposal, are provided each design task. Lead design engineers exist to supervise the process, assisted by company policy and established methodologies which have been proven successful in previous design endeavors.

In contrast, Georgia Tech's Aerial Robotics Design Team did not begin to form until after receipt of the AUVS competition announcement. Facilities, budget, and experience were extremely limited during earlier phases of the design cycle. Less than 43 weeks were available to develop the system, while prototype development in industry usually takes place over a period of years.

Student Engineers. *Given other academic requirements, it is nearly impossible to adequately compensate students involved in a design project of this magnitude.*

To compound difficulties presented by a shortened design cycle, student engineers were required by contest rules to make the "significant contribution to their entry"[27]. In addition, student team members were required to be enrolled "full-time" and scheduled for at least twelve hours per quarter/semester.

A review of student involvement revealed that less than 1.6 hours of the required twelve per school period were awarded as credit toward work on the aerial robotics project. Again, considering the academic engineer's industrial counterpart, approximately 13.3% of a student's work week was 'funded' by the aerial robotics project, while nearly 100% of the design engineer's time is compensated for work on design-related efforts.

Participating in a primarily volunteer role, classroom requirements must take precedence. *Project schedules which conflict with courses or other research become meaningless.* Unfortunately, the system engineer must acknowledge the conflict at the expense of the system.

Manpower.

The primary manpower deficiency of the Georgia Tech team was late involvement of key student electrical engineering expertise. 23.1% of knowledge about the design, represented by Level 4 Work Breakdown Structure components, was assigned the Mission Equipment Package group. Because they were not involved until early in Block 2, over 41% of the design cycle was lost.

Likewise, *the inability in academia to provide team continuity* resulted in loss of three critical team members to graduation at a crucial stage in the system's design.

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27. Association for Unmanned Vehicle Systems, "Official Rules", p. 2.

Facilities.

Integration efforts were not well served by the 'patchwork' nature of facilities available to the design team [Figure 13]. While the team attempted to implement electronic communications tools to assist in subsystem 'cross-talk', hardware lacked the multidisciplinary 'flavor' which likely would have eased integration efforts. Working primarily in discipline-specific facilities, time constraints periodically allowed the team to wander from multidisciplinary interaction to technical specialization. Team interaction was limited, for the most part, to group meetings and electronic mail.

Establishing some type of communications network would have reduced the impact of scattered lab space. However, a wide variance in knowledge of e-mail procedures resulted in abandonment of these initiatives. No common capability, as described in the successful tenets for implementation of concurrent engineering, was available.

What Was Right with the Design Environment?

Budget.

The team was successful, through innovative cost sharing methods, to finance the aerial robot's design within budget. Aggressive industry solicitation, advantageous partnerships, and industrial charity, when combined with generous university funding, allowed development of an advanced system for less than $20,000.

Experience Gained.

It was generally recognized that the ability to work on a hardware-oriented project while still in an academic environment provided a unique opportunity to most graduate and undergraduate engineers. A multitude of practical lessons learned, both from engineering

and team interaction standpoints, allowed unique understanding of the variety of technical specialties involved with the robot's design.

Was Application of Concurrent Engineering Techniques Effective?

Chapter 2 presented the reasons for applying concurrent engineering techniques to any project were to achieve higher quality at lower cost in shorter time. Having already addressed the quality issue through an evaluation of the AUVS assessments of system performance and just outlined the success enjoyed in building the system under budget, an evaluation of development time will be presented.

The complete Freedom of Design vs. Knowledge About the Design plot for the aerial robotics effort is shown in Figure 56. Figure 16 presented Schrage and Rogan's analysis of the qualitative effects on these curves through application of concurrent engineering methods. If the baseline curve represented the typical sequential design process, application of CE techniques should move the curve to right, increasing its slope in comparison to the baseline [Figure 16]. Conversations with Sobieski revealed, unfortunately, that these curves are strictly qualitative plots and that no formulae exist describing the 'typical sequential design process'. Therefore, unless a project is accomplished using both traditional sequential methods and concurrent engineering, comparison strictly on the basis of these curves is not possible. As direct comparison between the two design methodologies is not normally possible, what is accomplished, qualitatively, by the curve shift achieved through CE application?

Intersection of the Two Curves. The point where these curves cross corresponds to a time in the design process when knowledge of the design equals the remaining design

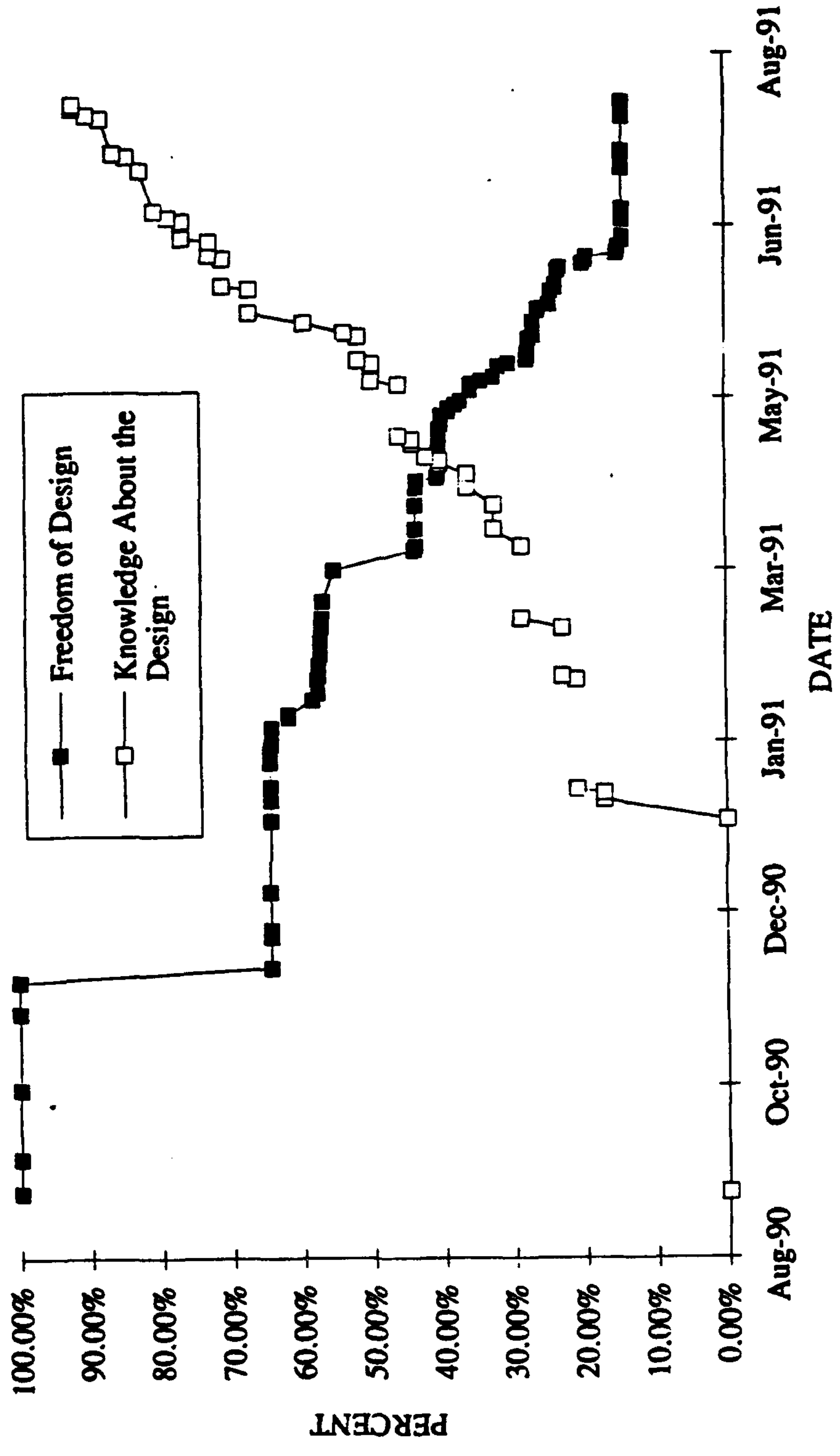

Figure 56 - Freedom of Design vs. Knowledge About the Design Plot for the Complete Development Cycle

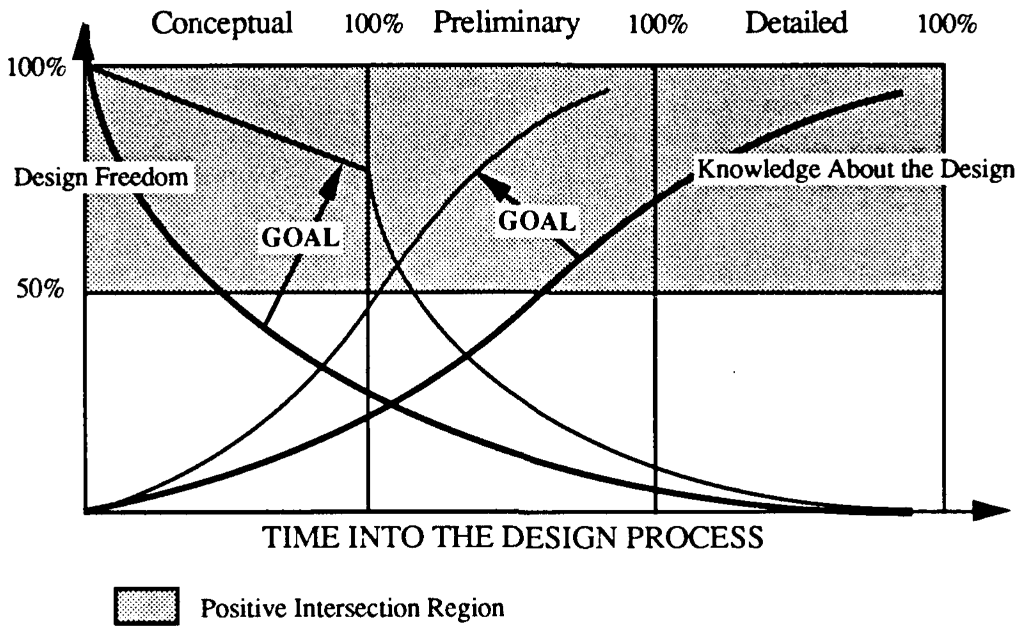

Figure 57 - Design Curve Intersection Relationship

freedom. This is a positive relationship when the intersection occurs above the 50% line, meaning that more than 50% of the design freedom remains to accomplish less than 50% of the design [Figure 57]. This figure shows how the shift described by Schrage and Rogan results in movement of the intersection point above the 50% mark. When this intersection occurs below the 50th percentile line, the project suffers a 'design deficit' where the team must engineer a larger percentile of the product than resources remain to accomplish that design. Such was the case with Georgia Tech's design effort on the aerial robot. This relationship is easier to understand if the '1-knowledge about the design curve', termed here the 'knowledge left to design', is plotted [Figure 58]. The 'knowledge left to design' plot can be considered analogous to a stack of bills which must be paid and the 'freedom of design' to a checkbook ledger. Figure 58's intersection occurs on July 15th, meaning the Tech team worked in a 'design deficit' for nearly 96% of the design cycle. Better

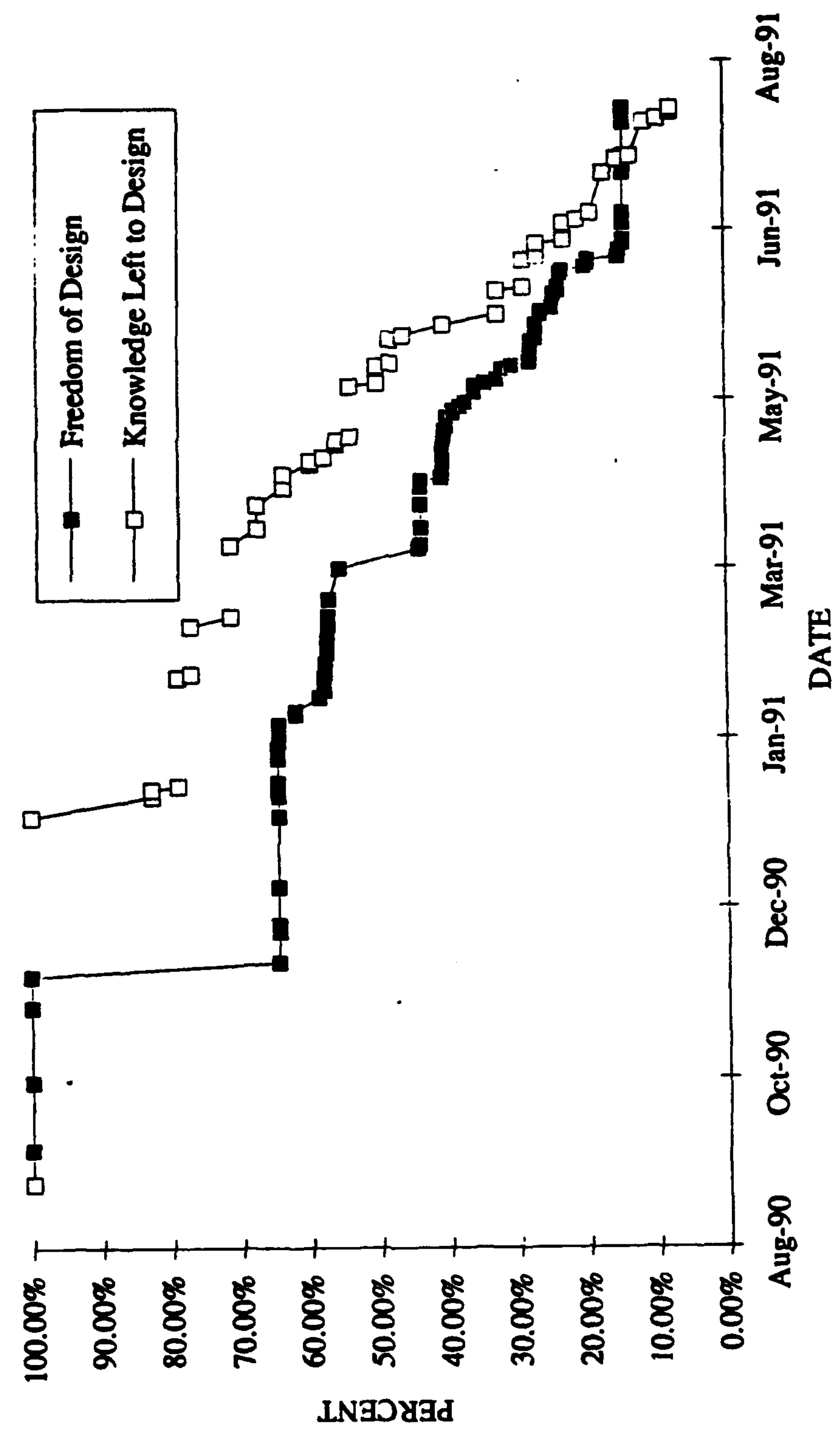

Figure 58 - The Georgia Tech Aerial Robotics Team's Design Deficit

application of concurrent engineering techniques to future projects should shift the knowledge about the design curve up, and the knowledge left to design relationship down, producing a surplus design environment earlier in the design cycle.

It is likely impossible to attain a complete design cycle in a surplus of knowledge to freedom. Almost intuitively, at some point in the conceptual design, an investment of freedom of design must be made in order to initiate the process. In this case, selection of the Bruiser could be likened to that investment while, more typically, identification of a powerplant on other aircraft systems normally becomes the first significant step toward refining a design during the preliminary stages.

CHAPTER VI

CONCLUSIONS

Why Did Quality and Development Time Suffer?:

Underlying the ten characteristics for successful implementation of concurrent engineering should be "a computing environment which allows a shared information database with open access to all participants in the CD process [which] can be used for automated configuration management and control"[28]. While recognized early by the team, this important requirement was never implemented.

In order for the team to succeed, *some type of computer bulletin board, either created to specifically support the aerial robotics design effort, or utilizing existing electronic mail capabilities, must be adopted.* Pugh [14] highlights electronic white boards, for example, as means to visualize large quantities of data which can be easily manipulated.

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28. Daniel P. Schrage, Concurrent Design: A Case Study, p. 11.

A Top-Down Design Approach Based on a Comprehensive Systems Engineering Process.

The team was relatively successful in establishing responsibility for subsystem development using a Work Breakdown Structure. Alignment of the team on specific hardware components, rather than on interfaces, created integration difficulties later in the design cycle. Although a Systems Engineering Management Plan (SEMP) was drafted, it lacked the depth necessary to truly be the 'cornerstone' management document it was intended to be.

Some time must be devoted to understanding system responsibilities. *Better attention to interface of subsystems, and components within subsystems, must be accomplished. Team realignment away from hierarchical system decomposition and oriented to system function, clear integration responsibilities, and mutually agreed upon system milestones must be incorporated into the team's SEMP.*

Strong Interface with the Customer.

While the Georgia Tech team enjoyed a geographical advantage in being located close to the competition's sponsor, quality assessments by the customer of fielded systems indicate this advantage was not adequately exercised. Inappropriate levels of importance applied to various customer requirements likely resulted in bypassing feasible design alternatives.

Wherever the customer is concerned, the competition sponsor must be consulted. If design choices are made based on customer requirements, the AUVS should have been given the opportunity to assist in developing and ranking key requirements.

QFD matrices should be completed as early in the design process as feasible. Much of the system block diagram obtained through detailed analysis of the quality function deployment tables and technical performance parameters could have been realized earlier.

Multifunctional and Multidisciplinary Teams.

The team was successful in obtaining key technical expertise in all critical specialties. In some cases, however, critical disciplines, like electrical engineering, were missing from the team for a significant period of time.

The new team should be realigned to function, rather than hardware component. Where possible, multidisciplinary groups, as subsets to the team, should be formed. A central facility must be established in order to ensure the team's multidisciplinary nature is optimized through interaction.

Design Benchmarking and Soft Prototyping.

As with the first competition, efforts at competitive benchmarking will likely be difficult. However, *further work in soft prototyping should be initiated as early as is feasible.* Use of computer solid models was shown effective in solving a variety of system geometric issues. Further work would likely compliment the recommended electroni database.

Simulation of Product Performance and Manufacturing and Support Processes.

Lack of available or applicable tools indicated much work is needed in this area, particularly so for unmanned aerial vehicles. *Simulation facilities should be utilized, where possible, existing automated design tools must be calibrated for this scale system, and manufacturing and support tools must be obtained and employed.*

Early Involvement of Subcontractors and Vendors.

Clearly defined responsibilities between the team and its affiliates must replace unwritten agreement. Undue reliance on perceived development responsibilities threatens the entire system.

Continuity of the Teams.

Care must be given to assignment of critical component development responsibilities to likely degree candidates. Further, a balance of undergraduate and graduate participation should continue in order to assure long-term interest in the project. New system engineers should be identified during the preceding cycle for the upcoming design period.

Practical Engineering Optimization of Product and Process Characteristics.

Where appropriate, *component optimization candidates should continue to be identified.* While unlikely, particularly in the academic environment, that significant optimization time will be available, an optimization plan must be in place.

Experiments to Confirm/Change High Risk Predictions Found Through Simulation.

Eventual application of Taguchi methods and other statistics-based quality techniques will require significant record-keeping efforts. *Detailed procedures to establish lessons learned logs, record reliability and maintainability data, and document the ongoing design cycle across all subsystems must formally be established in the SEMP.* Where applicable, availability of 'like' data should be pursued in order to more quickly establish significant information records on which quality tools may be applied. For example, use of aircraft maintenance data obtained from local R/C clubs may allow more statistically-significant analysis of helicopter maintenance and reliability trends.

Corporate Focus on Continuous Improvement and Lessons Learned.

The team should assign one or more engineers the responsibility of documenting ongoing design efforts. Again, formal procedures should be established in the SEMP. Both written and pictorial records should be kept. Where possible, use of 'default' record keeping systems, like electronic mail, should be used.

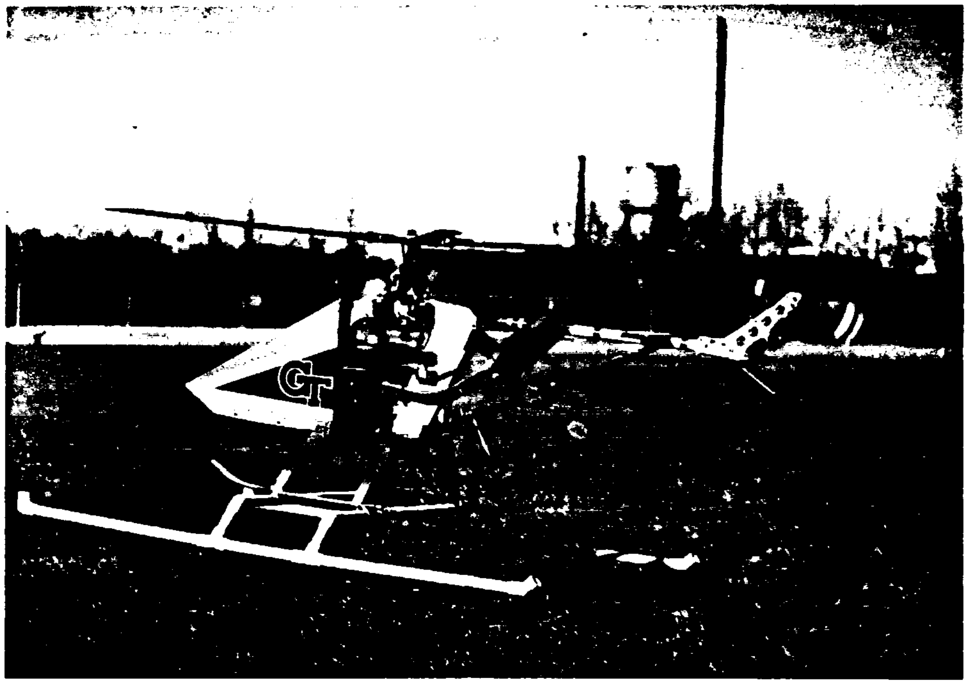
General.

Failure to understand the quality engineering tools and their application resulted in 'random' use during this initial phase. Winner [1] presents a table of nearly 25 quality engineering tools. An understanding of each of these tools, their application, and typical results would significantly aid the system engineer.

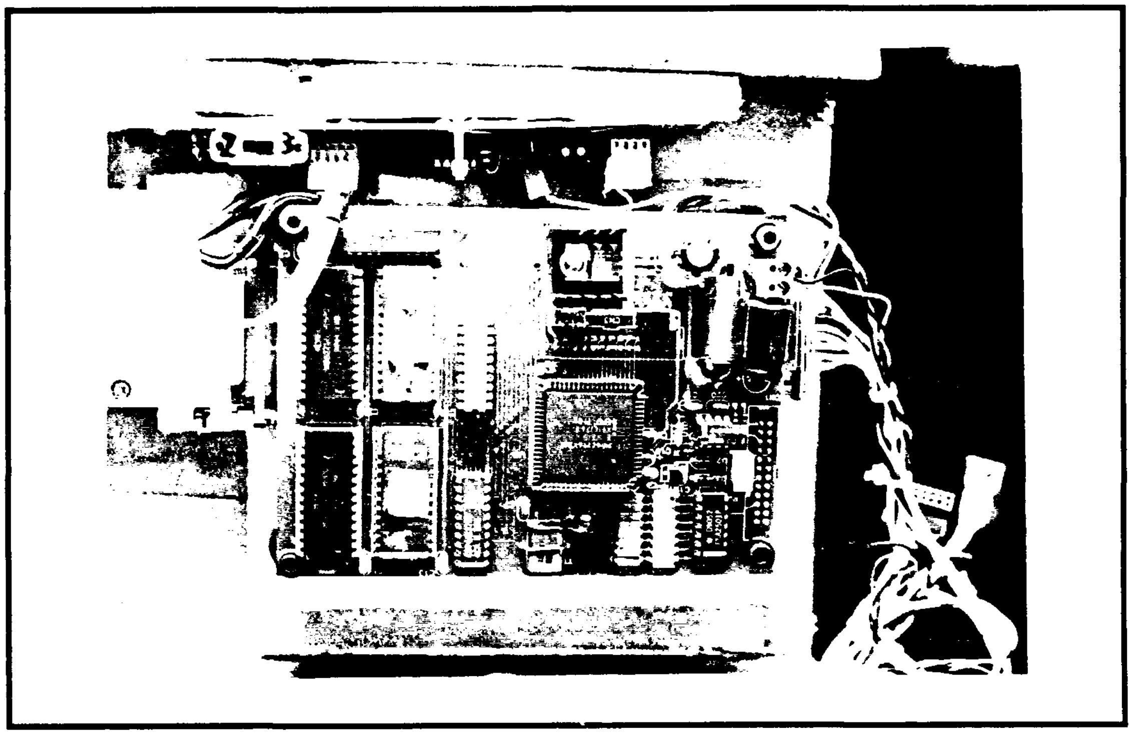
Lastly, Georgia Tech should seek every means to ensure students are able to continue participation in this event. Valuable hardware-oriented design experience and multidisciplinary exposure through the team enhance learning far beyond academic exercises driven by textbook problems.

APPENDIX 1

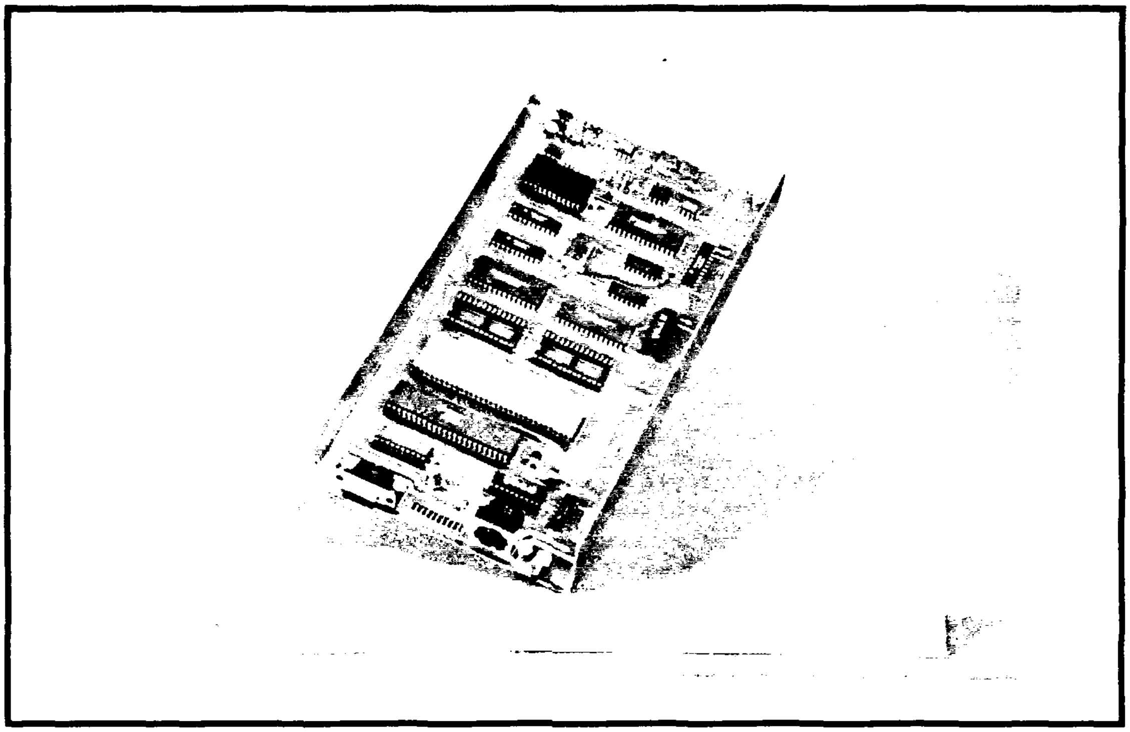
SELECTED SYSTEM EQUIPMENT DESCRIPTION



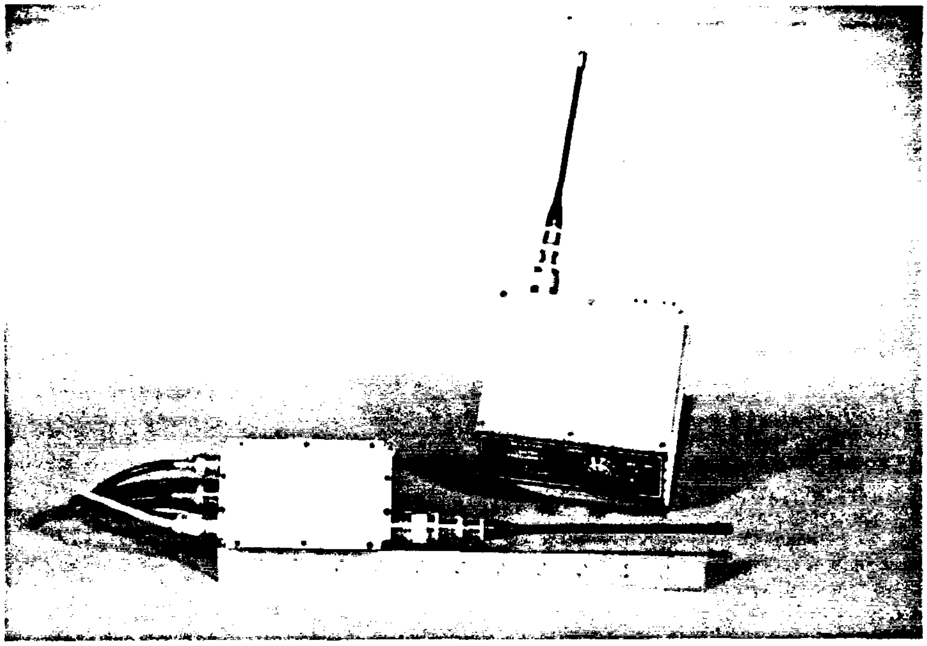
Nomenclature	Bruiser II Remotely-Piloted Vehicle
Manufacturer	Pacific RPV, Start-Up, Washington
Max Gross Weight (Takeoff)	40 pounds (estimated)
Empty Weight	23 pounds (estimated in AUVS configuration)
Power Plant	Serie ST 77i Super Tartan 3.95 Brake Horsepower (w/o tuned exhaust) 4.50 Brake Horsepower (estimated w/ tuned exhaust)
Rotor Diameter	60 inches
Height	19 inches (keel plate to top of main rotor hub)
L.ngth	75 inches (original forward fairing)
Width	28 inches (landing gear)



Nomenclature	Modified SASSYS-1 Auto Leveler
Pitch Position	$\pm$ 45 degrees
Pitch Rate	To 100° per second
Roll Position	$\pm$ 45 degrees
Roll Rate	To 100° per second
Position Accuracy	.1 degree
Yaw Rate	To 100° per second
Velocity Range	0 to 100 kilometers/hour for corrected position
Power Supply	12-16 volts DC at 450 mA
Weight	18 ounces
Spare Analog Inputs	3 at $\pm$ 10 volts range, 12 bit resolution
Options	RS-232 serial operation data output



Nomenclature	Stinger 70 Integrated Vision System
Manufacturer	Dickerson Vision Technologies, Atlanta, GA
Physical Dimension	10 inches x 5 inches x 1 inch
Weight	6.9 ounces (estimated)
Full Frame Rate	100/second (maximum)
Partial Frame Rate	1000/second (maximum)
Accuracy (small fiduciary)	1/20 pixel (RMS)
Resolution (small fiduciary)	1/200 pixel (RMS)
RAM Memory	96K bytes
ROM Memory	64K bytes
Processor	8 MHz 68000
Frame Size	165 x 192 pixels



Nomenclature

Airborne	ATS-410A Transmitter
Ground-Based	ATS-400 Receiver

Manufacturer TRON-Tek, Inc., Tulsa, Oklahoma

Physical Dimension

ATS-410A Transmitter	5 inches x 5 inches x 1.25 inches
ATS-400 Receiver	5 inches x 5 inches x 2 inches

Weight

ATS-410A Transmitter	1.5 pounds (estimated)
ATS-400 Receiver	1.6 pounds

Frequency 460 MHz

Power Output 1 Watt (30 dBm) $\pm$ 1 dBm

RF Impedance 50 Ohms

APPENDIX 2

GLOSSARY

AE - Aerospace Engineering

AHRS - Attitude Heading Reference System. The nomenclature for an attitude and rate sensor package manufactured by Watson Industries.

ARMCOP - A simulation package used to model vehicle stability and control characteristics developed by NASA.

ATDC - Advanced Technology Development Center

ATF - Advanced Tactical Fighter

AUVS - The Association for Unmanned Vehicle Systems. Sponsor of the First International Aerial Robotics Competition.

AV - Aerial Vehicle

baud - Computer transmittal rate in bits of information per second.

CAD - Computer-Aided Design

CALS - Computer-Aided Acquisition and Logistics Support

CAM - Computer-Aided Manufacture

CCRC - Cobb County Radio Control Club

CD - Concurrent Design

CE - Concurrent Engineering. May also be used as an acronym for Civil Engineering.

CoC - College of Computing

COMOK - Computerized Mock-up

D/A - Digital-to-Analog

DC - Direct-Current

DFA - Design for Assembly

DFM - Design for Manufacturability

DFT - Design for Test

DL - Data Link

DoD - Department of Defense

EE - Electrical Engineering

EPA - Environmental Protection Agency

ETB - Essential Task Breakdown

ETL - Effective Translational Lift

EQFD - Enhanced Quality Function Deployment. A second-general Quality Function Deployment method developed by Don Clausing at the Massachusetts Institute of Technology.

EXCOM - Executive Committee. A formal working group of the Georgia Tech Aerial Robotics Design Team composed of the lead engineer and faculty advisor from each participating school and industrial sponsors.

FFRRV - Free-Flight Rotorcraft Research Vehicle. An ongoing research project being conducted by the United States Army Aerostructures Directorate in Langley, Virginia.

GST - Guided Systems Technologies

GT - Georgia Tech

GTRI - Georgia Tech Research Institute

HLVS - High-Level Vision System

Hz - Hertz

IDA - Institute for Defense Analyses. Sponsor of one of the original Concurrent Engineering studies (Winner, et al).

I-DEAS - A computer simulation package which includes solid modeling capability.

ILS - Integrated Logistics Subsystem

IPD - Integrated Product Development. The General Dynamics Fort Worth-specific implementation of quality engineering.

IPR - In Progress Review. A formal design review.

IVS - Integrated Vision System

JPO - Joint Project Office. An organization established to jointly monitor unmanned aerial vehicle efforts by all branches of service within the Department of Defense.

Kbaud - Kilobaud

LLVS - Low-Level Vision System

ME -	Mechanical Engineering
MEP -	Mission Equipment Package. That portion of Georgia Tech's system which made up the aircraft's payload.
MIT -	Massachusetts Institute of Technology
MPCS -	Mission Planning and Control Station
NiCd -	Nickel-Cadmium
ORM -	Object Retrieval Mechanism
PCB -	Printed Circuit Board
PDOM -	Parameter Design Optimization Methods. Quality methodology developed by Dr. Genichi Taguchi.
PDS -	Product Definition Specification
QFD -	Quality Function Deployment. A graphical mapping technique which deploys the customer's desires to product and supporting process.
RAF -	Roswell Air Force. A metro-Atlanta radio-control club.
R/C -	Radio-controlled.
RFP -	Request for Proposal
RPV -	Remotely-Piloted Vehicle
SAS -	Stability Augmentation System
SE -	Systems Engineering
SEMP -	System Engineering Management Plan
SPC -	Statistical Process Control.
TACOM -	Tank-Automotive Command, United States Army
TANGO -	A circuit board layout tool.
TPM -	Technical Performance Measures
TQC -	Total Quality Control. The Japanese implementation of quality engineering.
UAV -	Unmanned Aerial Vehicle
UT -	University of Texas

VTOL - Vertical Take-Off and Landing

WBS - Work Breakdown Structure

WREK - Call letters for Georgia Tech's campus radio station.

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